Ruthenium Catalysed C-H Functionalisation of Heteroaromatics

Liu, Po Man

Award date:
2015

Awarding institution:
University of Bath

Ruthenium-Catalysed C-H Functionalisation of Heteroaromatics

Volume 1 of 1

Po Man Liu

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Chemistry

September 2014

COPYRIGHT

“Imagination is more important than knowledge”

Quoted by Albert Einstein , 1879 – 1955.

Publication List

1) O. Saidi, J. Marafie, A. E. W. Ledger, P. M. Liu, M. F. Mahon, G. Kociok-Kohn, M. K. Whittlesey and C. G. Frost, *J. Am. Chem. Soc.*, 2011, **133**, 19298-19301.

2) P. M. Liu and C. G. Frost, *Org. Lett.*, 2013, **15**, 5862-5865.

Abstract

Two methods of C-H functionalisation of sp^2 C-H bonds *via* ruthenium catalysis have been developed in this thesis. The first methodology is the preparation of *meta*-sulfonated heteroaromatics. Individual substrate optimisations were performed on various nitrogen containing heteroaromatics such as 2-phenylpyridine, 1-phenylpyrazole and benzo[*h*]quinoline. It was discovered that 2-phenylpyridine was the best substrate for C-H sulfonation with aryl sulfonyl chlorides and gave yields of 4 – 63% and provided functional handles allowing for further synthetic manipulations.

The second methodology developed is a ruthenium(II) catalysed *ortho*-C-H acylation of heteroaromatics. Initial optimisation was performed on 2-phenylpyridine with *ortho*-toluoyl chloride for C-H acylation and it was found tricyclohexylphosphine was the best ligand for this reaction. Unfortunately, the scope of this reaction is limited, as only a couple of aryl acid chlorides were compatible for the acylation of 2-phenylpyridine. This methodology was then applied to 1-phenylpyrazole and demonstrated the first example of C-H acylation of 1-phenylpyrazole with acid chloride as the coupling partner. C-H acylation of 1-phenylpyrazole is more versatile than 2-phenylpyridine, as the reaction scope is much broader. Various aryl and alkyl acid chlorides were compatible for the acylation of 1-phenylpyrazole derivatives and gave yields of 4 – 91%. Sterically hindered acid chlorides provided the higher yields, which is indicative of a steric acceleration during the reductive elimination step.

Ruthenium-substrate complexes were synthesised and employed in stoichiometric experiments under the *meta*-sulfonation and *ortho*-acylation conditions independently, to attempt to elucidate the mechanistic pathways of these two reactions. ^{1}H NMR spectroscopy on the *meta*-sulfonations of 1-phenylpyrazole and benzo[*h*]quinoline complexes indicated the formation of sulfonated ruthenium-substrate complexes, where the sulfone is substituted *para* to the ruthenium-carbon bond. C-H activation of 1-phenylpyrazole with a ruthenium-phosphine complex was attempted, and found it was difficult to synthesise the C-H activated substrate-ruthenium complex in the presence of phosphine ligands.

Table of Contents

Acknowledgements

First and foremost, I wish to thank my supervisor, Professor Christopher Frost for giving me this opportunity to do a PhD. I thank Chris for his constant support and guidance throughout my studies. Thank you for always finding time to discuss my ideas with me and encouraging me to lead my own research.

I would like to thank all members of the Frost group, past and present. I would like to thank Dr Hannah Edwards and Dr Ourida Saidi for both personal and professional, for helping me to settle in when I first joined in the group and provided me guidance on my work during my first year of PhD. I thank Dr Jonathan Sharpe, Dr Will Reynolds and Sean Goggins, for answering many of my silly questions, and made working in the lab fun. Also, I thank Will for proofreading my thesis. I thank Dr Steve Flower for his hyperactive mood, Dr Jimmy White for being Jimmy and Dr Patricia Marcé-Villa for the help and guidance on the mechanistic study, and providing the work on the *meta*-sulfonation kinetics reaction profiles. Special thanks to Dr Barrie Marsh, you've been more than a postdoc to me, more like an older brother always helping me out and building my self-confidence. Thanks for proofreading my thesis and teaching me many things in chemistry and life as well as introducing me to the urban dictionary. I thank Will Mahy for his wonderful cakes and Andy Paterson for his awful humour and corrupting me with urban phrases that I will make sure not to use. Most of all, thank you all for making these last 4 years memorable.

Also thanks to John Lowe for his NMR expertise and Mike Whitelessey for always solving my many problems with the 500 MHz NMR machine. Thanks also go to Anneke Luben for MS, Gabriele Kociok-Köhn for all the crystal structures in chapter 2 and Mary Mahon for all the crystal structures on my ruthenium complexes.

During my time at Bath, I have made some invaluable friends, Suying, Junzhe, Sabrina, LiLi, Elvis and Yi, thank you for being great friends and I thank Suying for always giving me food. I would also like to thank my friends in London, especially Shaun for the phone calls of my complaints about my chemistry not working and other things.

Most importantly, I would like to thank my family for their unconditional support and faith in me to complete my studies.

Abbreviations

Å	angstrom
Ac	acetyl
Ad	adamantyl
^{t}AmOH	*tert*-amyl alcohol
Anal.	analytical (spectroscopy)
app	apparent
aq.	aqueous
Ar	aryl
atm	atmospheres
BINAP	2,2’-bis(diphenylphosphino)-1,1’-binaphthyl
bipy	2,2'-bipyridine
Bn	benzyl
br	broad
Bu	butyl
^{n}Bu	*n*-butyl
^{s}Bu	*sec*-butyl
^{t}Bu	*tert*-butyl
°C	degrees Celsius
cat.	catalytic
calcd.	calculated
C-H	carbon-hydrogen bond
C-M	carbon-metal bond

cm^{-1}	wavenumber(s)
CMD	concerted metallation deprotonation
COD	1,5-cyclooctadiene
COE	cyclooctene
COSY	correlation spectroscopy
Cp*	pentamethylcyclopentadienyl
Cy	cyclohexyl
Cy JohnPhos	(2-biphenyl)dicyclohexylphosphine
°	degrees
δ	chemical shifts in part per million downfield from tetramethylsilane
d	doublet (spectral)
dba	dibenzylideneacetone
DBN	1,5-diazabicyclo[4.3.0]non-5-ene
DCE	dichloroethane
dec.	decomposition
DFT	density functional theory
DG	directing group
DMA	dimethylacetamide
DMAP	4-dimethylaminopyridine
DME	dimethoxyethane
DMF	*N,N*-dimethylformamide
DMSO	dimethylsulfoxide
DPPE	1,2-bis(diphenylphosphino)ethane
dppf	1,1'-bis(diphenylphosphino)ferrocene

dtbpy	4,4'-di-*tert*-butyl bipyridine
equiv	equivalent(s)
ESI	electrospray impact
Et	ethyl
EtOAc	ethyl acetate
g	gram(s)
Gly	glycine
h	hours
HASPO	heteroatom-substituted secondary phosphine oxide
hept	heptet (spectral)
^{n}Hex	*n*-hexyl
HFIP	hexafluoro-2-propanol
HMBC	Heteronuclear Multiple Bond Correlation
HRMS	high resolution mass spectroscopy
HSQC	Heteronuclear Single Quantum Coherence
Hz	hertz
^{i}	*iso*
Ile	isoleucine
IPA	*iso*-propyl alcohol
IPr-HCl	1,3-bis(2,6-di*iso*propylphenyl)imidazolium chloride
IR	infrared
J	coupling constant in NMR spectroscopy
L	ligand or litres
LC-MS	liquid chromatography-mass spectrometry

µ	micro
m	milli; multiplet (spectral)
M	molar, moles per litre
M^+	parent molecular ion
m	*meta* to the directing group of the aromatic ring
Me	methyl
MeCN	acetonitrile
Mes	mesityl
MHz	megahertz
min	minute(s)
MO	molecular orbital
mol	moles
mpt.	melting point
MS	molecular sieves; mass spectrometry
m/z	mass to charge ratio (in mass spectrometry)
naphth	naphthalene
NBS	*N*-bromo succinimide
NMP	*N*-methylpyrrolidone
NMR	nuclear magnetic resonance
o	*ortho* to the directing group of the aromatic ring
^{n}Oct	*n*-octyl
p	*para* to the directing group of the aromatic ring
PEPPSI-IPr dichloride	[1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidine](3-chloropyridyl)palladium(II)

Ph	phenyl
pin	pinacol
Piv	pivaloyl
ppm	part(s) per million
^{i}Pr	*iso*-propyl
PrCN	butyronitrile
Py	pyridine
Pybox	pyridine(bis)oxazoline ligand
q	quartet (spectral)
quint.	quinetet (spectral)
R_f	retention factor (in chromatography)
rt	room temperature s
s	singlet (spectral)
S_EAr	electrophilic aromatic substitution
SM	starting materials
SPhos	2-dicyclohexylphosphino-2',6'-dimethoxybiphenyl
^{t}	*tert*
t	triplet (spectral)
T	template
TBAF	tetrabutylammonium fluoride
TBDMS	*tert*-butyldimethylsilyl
temp	temperature
Tf	trifluoromethanesulfonyl
TFA	trifluoroacetic acid

TFAA	trifluoroacetic anhydride
THF	tetrahydrofuran
TIPS	tri*iso*propylsilyl
TLC	thin layer chrmatography
TMP	2,2,6,6,-tetramethylpiperidide
TMS	tetramethylsilane
Ts	4-toluenesulfonyl
Val	valine
vs	versus
Xantphos	4,5,-bis(diphenylphosphino)-9,9-dimethylxanthene
XPhos	2-dicyclohexylphosphino-2',4',6'-triisopropylbiphenyl

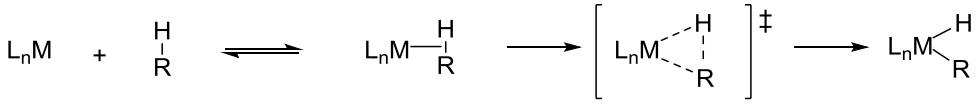
Chapter 1. Introduction

Direct and selective transformation of unfunctionalised feedstocks into complex molecules represents an important goal of synthetic organic chemistry. Over the past few decades, transition metal catalysed C-H functionalisation has revolutionised the field of organic synthesis.[1-3] Unlike traditional transition metal cross-coupling reactions, C-H functionalisation removes the necessity for pre-functionalised reagents and in addition avoids the formation of potentially harmful by-products. Furthermore, reactions' using the cleavage of C-H bonds are also more atom economical and provide opportunities to develop novel retrosynthetic pathways and efficient reaction sequences.[4-20]

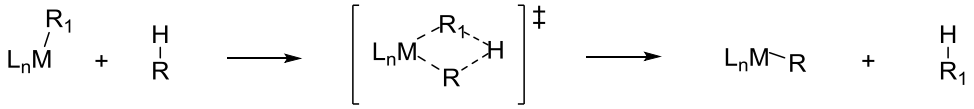
However, with this methodology there are certain key challenges to overcome: activation of the C-H bond, achieving site selectivity in the presence of multiple C-H bonds, performing the reaction catalytically and under mild reaction conditions and achieving an asymmetric variant. It is known that C-H bonds have high bond dissociation energies. For example, methane has the dissociation energy of 105 kcalmol^{-1}, whereas for the inert arene benzene is 110 kcalmol^{-1}.[21] C-H bond cleavage can be achieved by reacting transition metals with C-H bonds to produce C-M bonds; this process is known as C-H activation. The resulting C-M bond is more reactive than the C-H bond counterpart and can be transformed with new functional groups. The mechanism of the C-H bond activation is dependent on the nature of the metal fragment, therefore factors such as substrate, solvent, transition metal, additives and ligands all have an impact on the C-H metallation. There are four proposed mechanisms: (i) oxidative addition with electron rich late transition metal, (ii) σ-bond metathesis with early transition metal, (iii) electrophilic activation in electron deficient late transition metal and (iv) Lewis-base assisted metallation (Scheme 1).[12, 22-28]

To achieve oxidative addition, the reactive complex must have an empty σ-type molecular orbital (MO) and a high energy MO with a pair of electrons that can be transferred from the metal into the σ* orbital of the C-H bond during the oxidative addition reaction (i). This is a nucleophilic process and the metal oxidation state increases by 2 units. If the mechanism operates *via* an σ-bond metathesis, the reactive species must have vacant acceptor MOs to stabilise the transferred σ-bond electron pair in the transition state (ii). Electrophilic activation takes place in the presence of an electron deficient or cationic complex and undergoes reductive addition rather than oxidative addition (iii). A base-assisted C-H activation is facilitated by a coordinated or free base, often a carbonate or carboxylate ligand which can accept the leaving proton (iv).

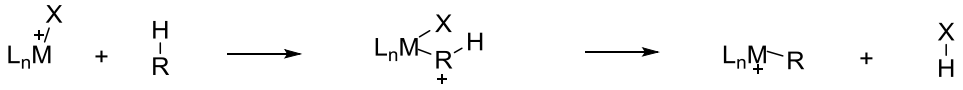
(i) oxidative addition



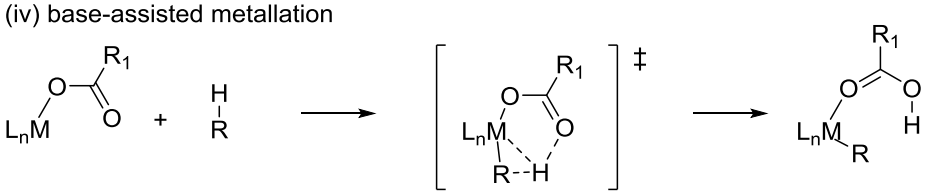
(ii) σ-bond metathesis



(iii) electrophilic substitution



(iv) base-assisted metallation



Scheme 1

Selective C-H functionalisation can be achieved with the use of a coordinating ligand, acting as a chelating/directing group that binds to the metal centre and selectively delivers the catalyst to a proximal C-H bond. The directing group is usually already installed in the substrate. Directing groups such as amides, carboxylic acids, ketones and heteroaromatics for example, pyrazoles and pyridines have been employed in C-H functionalisation reactions. The drawback is that the reaction may not be general to all substrates.

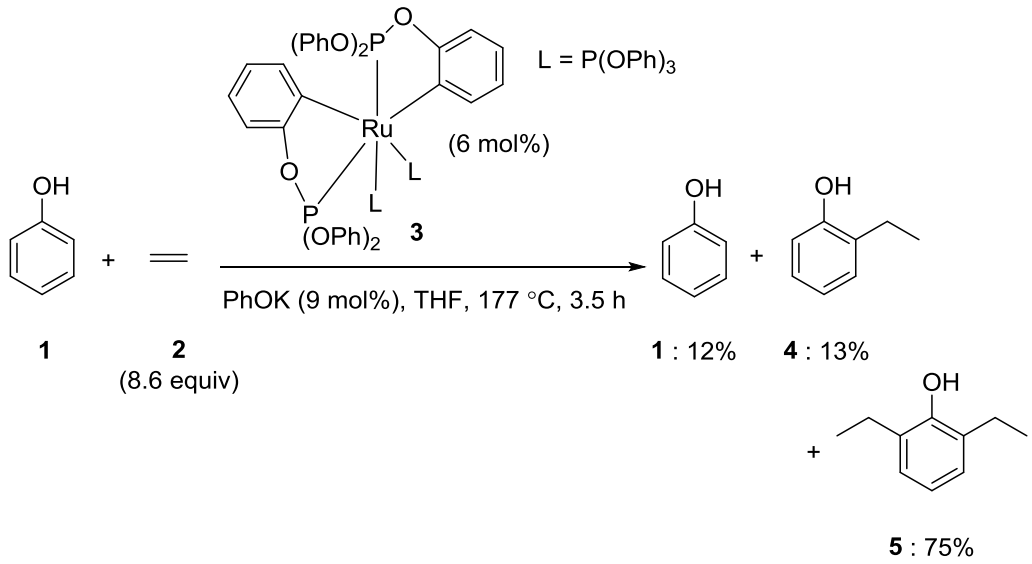
Transition metals such as Ir, Pd, Pt and Rh can undergo cyclometallation under stoichiometric conditions and most of the early work on catalytic C-H functionalisation reactions was carried out with Pd and Rh catalysts. Palladium catalysts such as $Pd(PPh_3)_4$ of Pd(0) oxidation state and $Pd(OAc)_2$, $PdCl_2$, $Pd(COD)Cl_2$ and $Pd(MeCN)_2Cl_2$ of Pd(II) oxidation state are commonly used as catalysts, or employ a Pd(II) catalyst in the presence of an oxidant to achieve Pd(0) catalysis. Both Rh(I) and Rh(III) complexes have also been employed in catalytic C-H functionalisation, Rh(I) catalyst's for example $RhCl(PPh_3)_3$ $[RhCl(COE)_2]_2$ and $[RhCl(COD)]_2$ and Rh(III) complexes such as $[Cp^*RhCl_2]_2$. However, these catalysts are expensive and a more cost effective option is desirable. For the past two decades Ru(0) and Ru(II) catalysts have emerged as a cheaper alternative for

performing many catalytic C-H functionalisations.[27] Moreover, Ru(II) complexes are easy to prepare and are often more stable catalysts that can perform a variety of reactions.

1.1. Ru(0) catalysed sp^2 C-H functionalisation

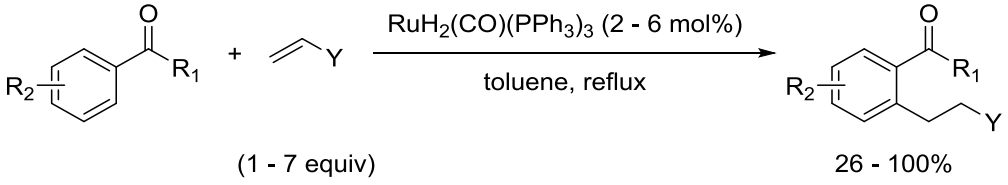
1.1.1. Ru(0) catalysed sp^2 C-H alkylation

One of the first examples of Ru-catalysed C-H functionalisation was developed by Lewis and Smith in 1986.[29] Phenol **1** was alkylated with ethylene **2** in the presence of a catalytic amount of a ruthenium phosphite complex **3** and potassium phenoxide as base. However, the reaction was carried out under harsh reaction conditions at 177 °C. The efficiency of the reaction was also poor, with a mixture of mono- **4** and di-alkylated **5** *ortho*-products being formed as well as some starting materials (Scheme 2).



Scheme 2

A notable advance was achieved by Murai and co-workers in developing a general method for *ortho*-alkylation of aromatic ketones with good efficiency and regioselectivity.[30] This was the first example of chelation-assisted C-H functionalisation. Aromatic ketones were alkylated in the presence of an olefin with $RuH_2(CO)(PPh_3)_3$ in toluene under reflux (Scheme 3). The ruthenium catalyst $RuH_2(CO)(PPh_3)_3$ is formally a ruthenium(II) complex, in the reaction it loses molecular H_2, to form the active Ru(0) species which catalyses the reaction.



(1 - 7 equiv) 26 - 100%

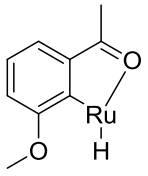
R_1 = Me, OMe, ^{t}Bu
R_2 = H, Me CF_3, F, OMe, NMe_2, naphth
Y = $SiMe_3$, $Si(OEt)_3$, Me, ^{t}Bu

Scheme 3

The authors discovered that ruthenium complexes containing three triphenylphosphine (PPh_3) ligands are essential for the reaction to proceed and that the most effective catalysts were $RuH_2(CO)(PPh_3)_3$ and $Ru(CO)_2(PPh_3)_3$. This reaction is efficient; as in a majority of cases the products were obtained in quantitative yields. Also a wide range of olefins are compatible, including ethylene, *tert*-butylethylene, styrene derivatives, vinyl silanes and 1,1-disubstituted alkenes. However, this reaction is limited to terminal alkenes only and olefins containing allylic hydrogens can easily isomerise which leads to undesired side products.

The reaction tolerates a wide variety of functional groups on the aromatic ring such as dimethylamino, methoxy, trifluoromethyl, methyl, fluoro and acetal. In addition, heteroaromatic ketones such as thiophenes can be utilised.

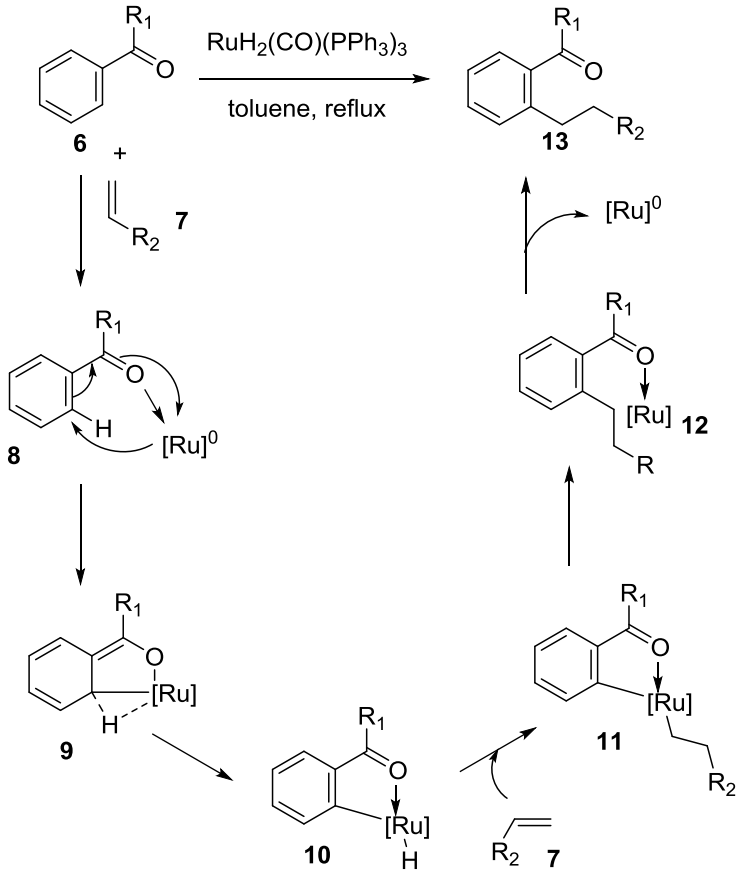
Selectivity can be further controlled by the presence of substituents on the aryl ring. In the case of *meta*-substituted acetophenone two different reaction sites are available. Steric hinderance usually controls the regiochemistry, directing C-C bond formation on the least congested site. However, when the *meta*-substituent is a methoxy or a fluoro group, alkylation takes place on the most sterically hindered site.[31, 32] This is due to coordination of the substituent to the metal, which directs the alkylation to the sterically congested site (Scheme 4).[33, 34]



Scheme 4

Murai and co-workers proposed that the first step involves the Ru catalyst eliminating H_2 upon heating to form an active Ru(0) species for the catalysis and hydrogenation of the alkene **7**. Coordination of Ru(0) to the oxygen of aryl ketone **6** aids the Ru(0) to oxidatively insert to the *ortho* carbon atom of the phenyl ring *via* nucleophilic attack, followed by migration of hydrogen

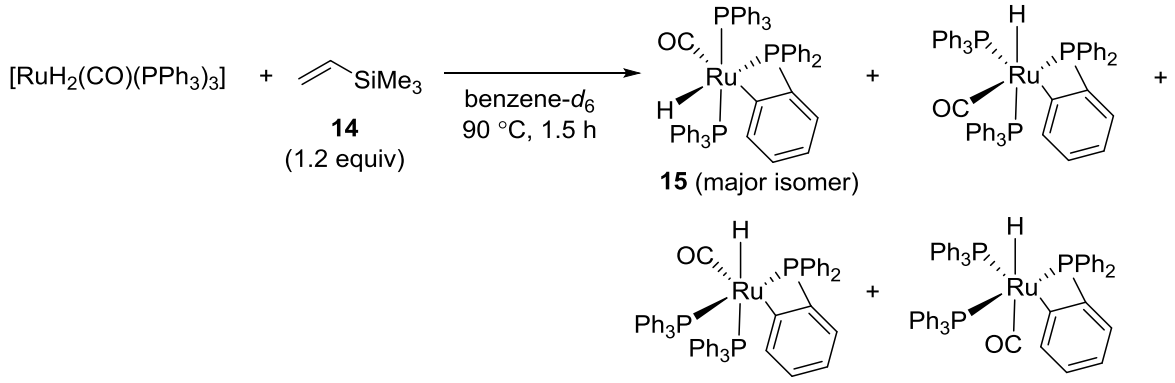
to the ruthenium centre. Then insertion of olefin **7** into Ru-H bond **11** followed by nucleophilic attack of the alkyl group on the Ru to the *ortho* carbon to form a new C-C bond **12.** This hypothesis was confirmed by DFT calculations by Morokuma and Koga (Scheme 5).[35]



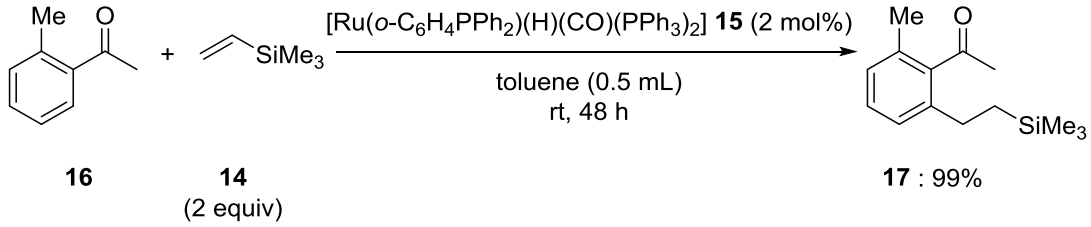
Scheme 5

In a separate study, Brookhart and Lenges analysed the reaction of acetophenone with alkenes with a Rh catalyst.[36] The mechanistic experiments revealed that the C-H bond cleavage of the aromatic ring does not require the pre-coordination of the carbonyl group to the metal. However, coordination of the carbonyl group is essential for the C-C bond formation as revealed by mechanistic studies.[31, 37, 38]

In 2010, Murai and co-workers carried out mechanistic studies and found that treatment of $RuH_2(CO)(PPh_3)_3$ with trimethylvinylsilane **14** at 90 °C formed an activated complex Ru(*o*-$C_6H_4Ph_2$)(H)(CO)$(PPh_3)_2$ **15** as a mixture of four geometric isomers (Scheme 6).[39] This activated complex **15** is able to catalyse the C-H/olefin coupling of *ortho*-methylacetophenone **16** with vinylsilane **14** at room temperature for 48 hours and obtained the *ortho*-alkylated product **17** in 99% yield (Scheme 7).

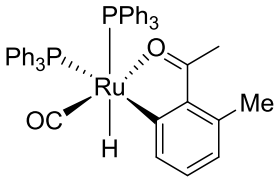


Scheme 6



Scheme 7

When the activated complex was subjected to catalytic conditions, the ^{1}H, ^{13}C and ^{31}P NMR spectra revealed the presence of an *ortho*-ruthenated aromatic ketone complex bearing a carbonyl ligand as an intermediate, which suggests that the carbonyl ligand is involved in the catalytic cycle (Scheme 8).

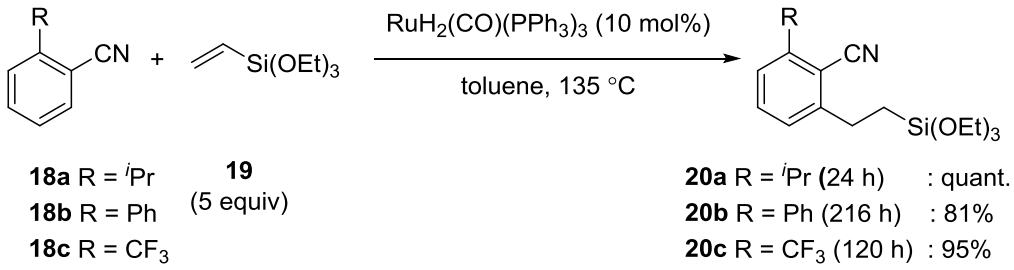


Scheme 8

Furthermore, a deuterium labelling experiment of acetophenone and acetophenone-d_5 with vinyl silane obtained a KIE of 1.02; this is a small KIE value that indicates the C-H bond cleavage is not the rate-limiting step, which is in agreement with the DFT study by Morokuma and Koga. Scrambling of H/D was observed between d_5-acetophenone and vinyl silane that indicates the rate-determining step is the C-C bond formation and that each of the steps prior to reductive elimination is in equilibrium.

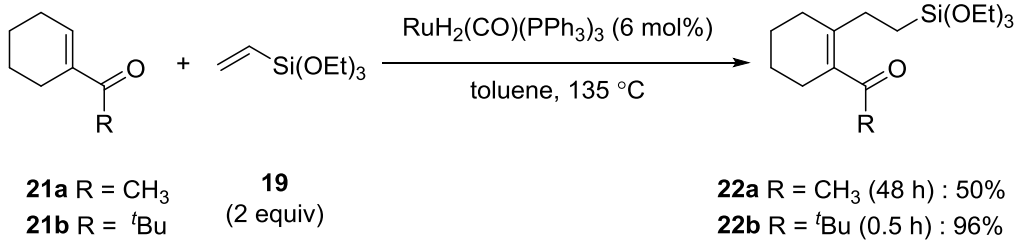
The Murai reaction can be applied to a variety of directing groups including aromatic aldehydes, esters, ketones and nitriles. [40-43] Unlike acetophenone, the other substrates were less reactive

towards olefins and for most of the cases; reaction only took place if the olefin was a vinyl silane. Aromatic nitriles react with the ruthenium *via* the π-coordination of the nitrile to the ruthenium.[42] Also, the reactivity of the aromatic nitriles **18** are much poorer, requiring higher catalyst loading of 10 mol% to afford the coupling product in a good yield. This was evident when there are *ortho*-substituents on the aromatic nitriles; depending on the substituent, the reaction can take over a week to obtain a good yield (Scheme 9).



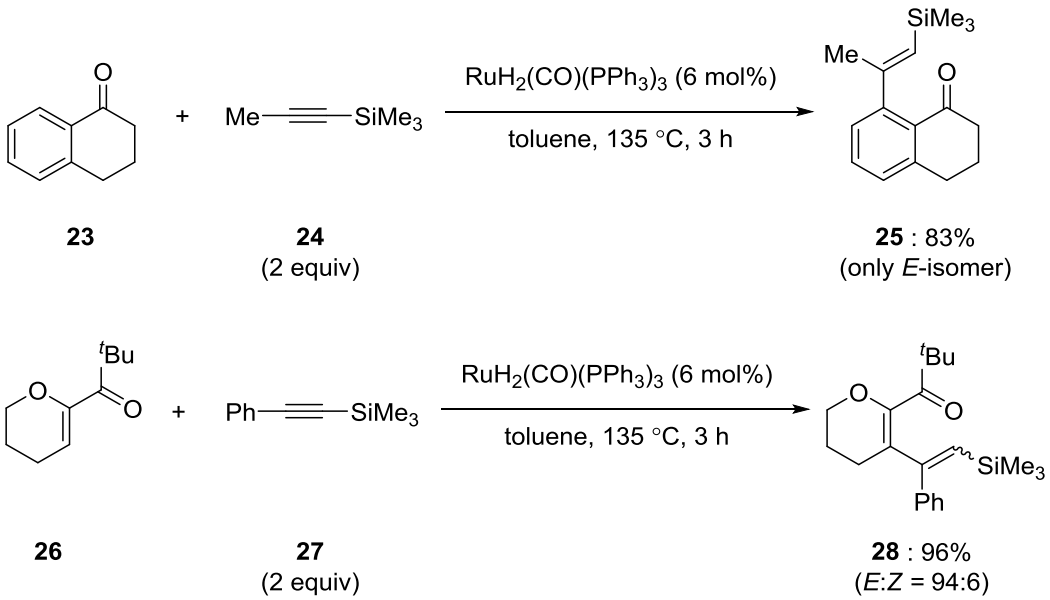
Scheme 9

In addition to aromatic ketones, α,β-enones are also suitable substrates for the C-H insertion reactions allowing for functionalisation of the β-C-H bonds.[44] For the acyclic enones, the reaction is most efficient with a bulky enone such as pivaloylcyclohexene **21b**, which gave the coupling product **22b** in near quantitative yield in 30 minutes. In contrast, the acetylcyclohexene **21a**, required a longer reaction of 48 hours, to only yield 50% of product **22a** (Scheme 10). Various heterocyclic enones such as furan, hydropyran and dihydropyran reacted well with triethoxyvinylsilane and obtained in good to quantitative yields. Various alkenes can be reacted with the enones such as α-methylstyrene, trimethylvinylsilane and vinylcyclohexane, and all obtained the corresponding products in excellent yields.



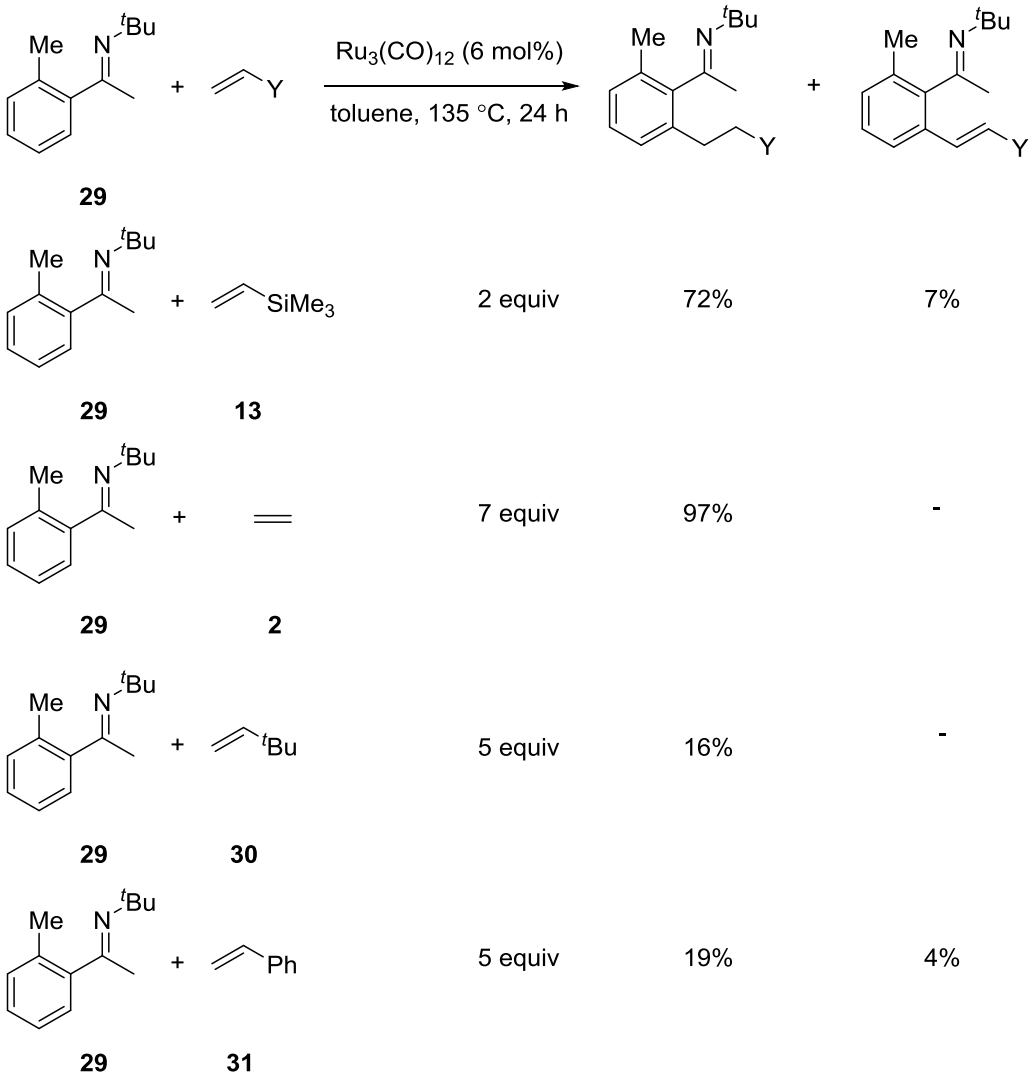
Scheme 10

The same catalyst can be applied to cyclic aromatic ketones **23** and enones **26** with alkynes to afford the *ortho* alkenylated product.[45, 46] In most of the cases, the products are isolated as a mixture of the *E* and *Z*-isomers; normally the *E*-isomer is the major product (Scheme 11).



Scheme 11

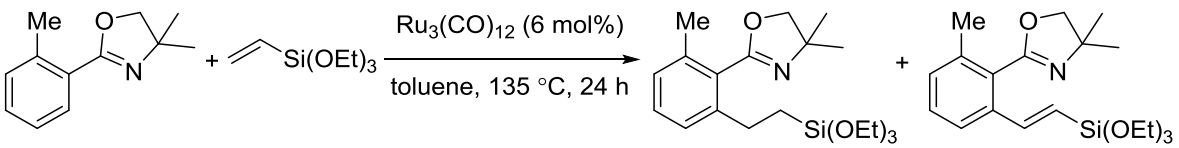
Contrastingly the change of directing group from a carbonyl to an imine requires a change of catalyst to make the alkylation to work efficiently.[47] $Ru_3(CO)_{12}$ was found to be the most effective catalyst with imines and aldimine substrates. It is noteworthy, that $Ru_3(CO)_{12}$ was a poor catalyst for the C-H alkylation for the carbonyl group based directing groups. The use of the *tert*-butyl group on the imine provides the steric bulk surrounding the nitrogen, which suppresses further functionalisation on the aromatic ring. The reaction scope was limited, with vinyl silane **14** giving the best yield. Ethylene **2** was a good coupling partner and obtained in near quantitative yield. Styrene **31** and *tert*-butylethylene **30** also gave the corresponding alkylated product but in a much lower yield (Scheme 12).



29 **29** **13** **29** **2** **29** **30** **29** **31**

Scheme 12

Under the same reaction conditions aryloxazoline **32** reacted with triethoxyvinylsilane **19** and obtained the dehydrogenated coupling product **33b** as the major product (Scheme 13).[48] It was suggested by the authors that the product was formed as a result of insertion of the olefin into the ruthenium-carbon bond followed by β-hydride elimination.

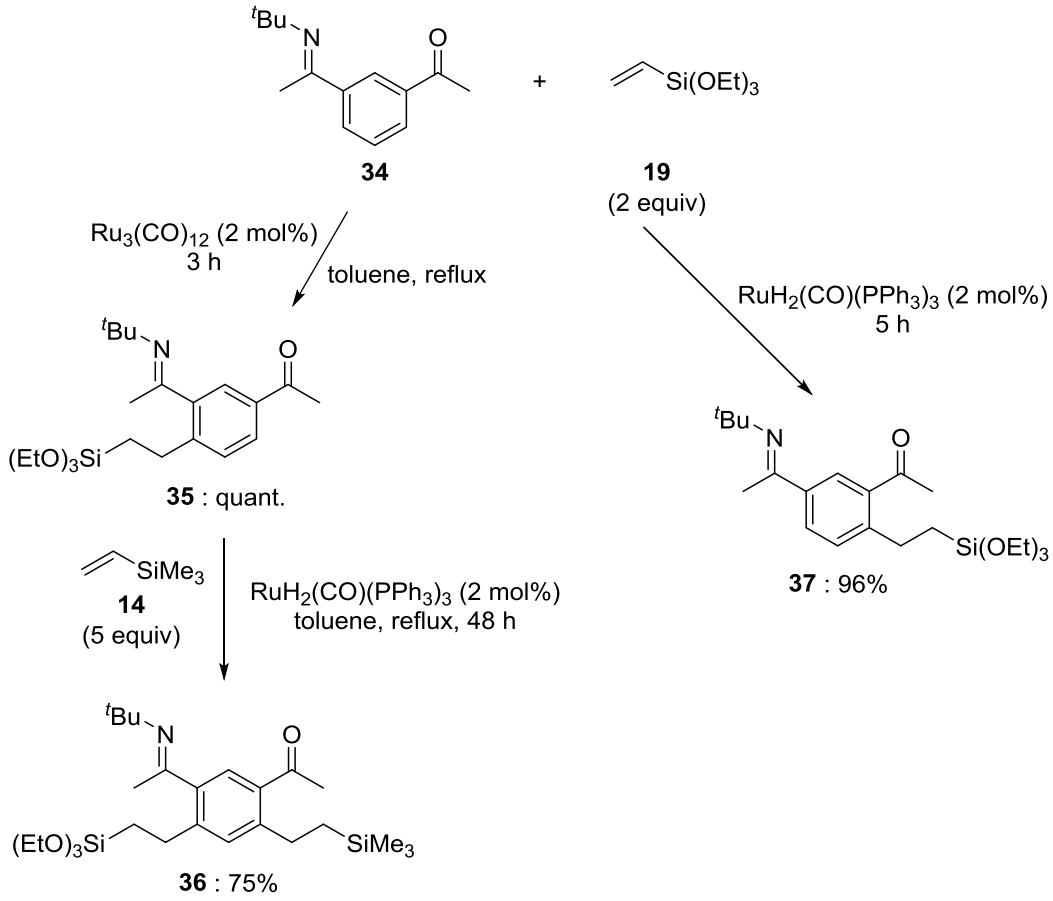


32 **19** (5 equiv) **33a** : 10% **33b** : 87%

Scheme 13

In the presence of two directing groups, an imino and an acetyl group, such as substrate **34**, the site-selectivity can be tuned depending on the catalyst and olefin used. Murai and co-workers

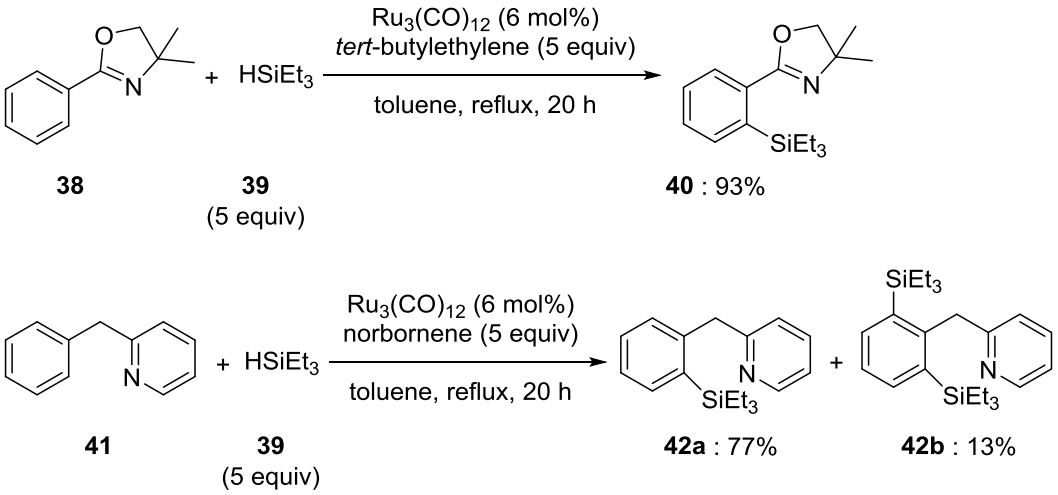
have demonstrated a sequential reaction,[49] in the presence of both directing groups. $Ru(H_2)(CO)(PPh_3)_3$ was directed by the carbonyl group to add across an olefin, *ortho* to the carbonyl group. Whereas, $Ru_3(CO)_{12}$ was efficient in catalysing the alkylation *ortho* to the imino group (Scheme 14).



Scheme 14

1.1.2. Ru(0) catalysed sp^2 C-H silylation

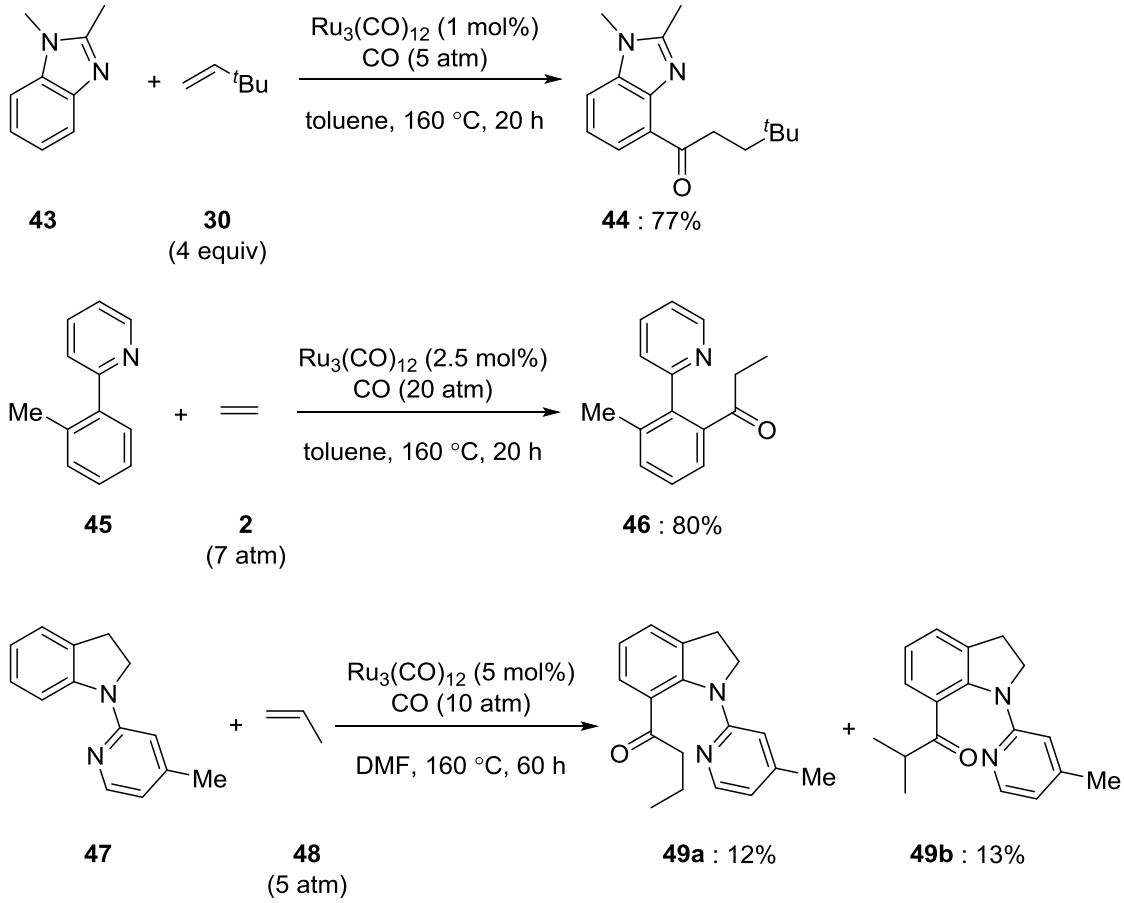
Murai and co-workers have extended the reaction scope to allow silylation of C-H bonds to obtain heteroarylsilanes using $Ru_3(CO)_{12}$ as the catalyst and hydrosilanes **39** as the coupling partner.[50, 51] The use of an olefin such as norbornene or *tert*-butylethylene is essential, as it acts as a hydrogen scavenger in this reaction (Scheme 15).



Scheme 15

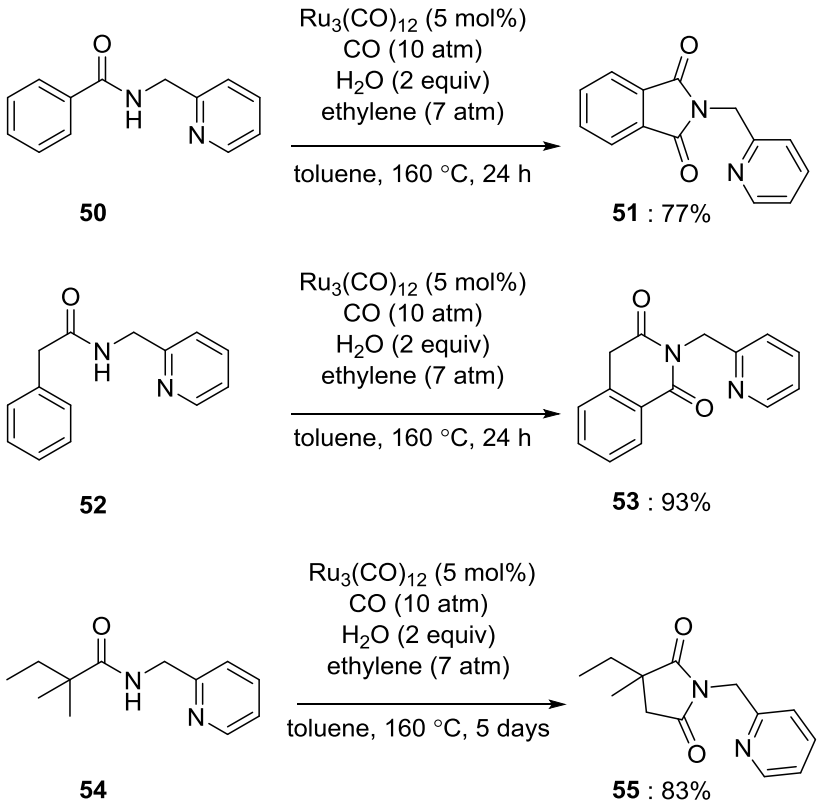
1.1.3. Ru(0) catalysed sp^2 C-H carbonylation

Murai and co-workers have also exploited $Ru_3(CO)_{12}$ as a catalyst for carbonylation reactions, with the use of a sp^2 nitrogen atom as the coordinating group for the transformation of the arene to an acylated product in the presence of an olefin and an atmosphere of carbon monoxide (Scheme 16).[52-61] The advantage of carbonylation is that the regioselectivity of the products is different from that of Friedel-Crafts acylation, however only aliphatic products can be obtained *via* this method.



Scheme 16

Recently, the Chatani group developed the ruthenium-catalysed cyclocarbonylation of *ortho* C-H bonds of aromatic amides to give phthalimides (Scheme 17).[62-64] The same chemistry is applicable to aryl acetamides and unactivated sp^3 C-H bond to afford succinimides. The key to the reaction is the 2-pyridinylmethyl amino moiety that acts as a *N,N*-bidentate ligand to form a dinuclear ruthenium complex with $Ru_3(CO)_{12}$ and this dinuclear complex can be used as a catalyst, but the efficiency of the complex as a catalyst diminishes in the absence of water. It was hypothesised that the role of water is to activate the dinuclear complex from its resting state to be able to participate in the catalytic cycle *via* the water-gas shift reaction. Furthermore, ethylene is essential in the reaction; the authors suggested that ethylene functions as a hydrogen acceptor in the catalytic cycle. Interestingly, the reaction rate of sp^3 C-H bond was slower in comparison with sp^2 C-H bond; a long reaction time of 5 days is needed to obtain the desired product **55** in good yield.

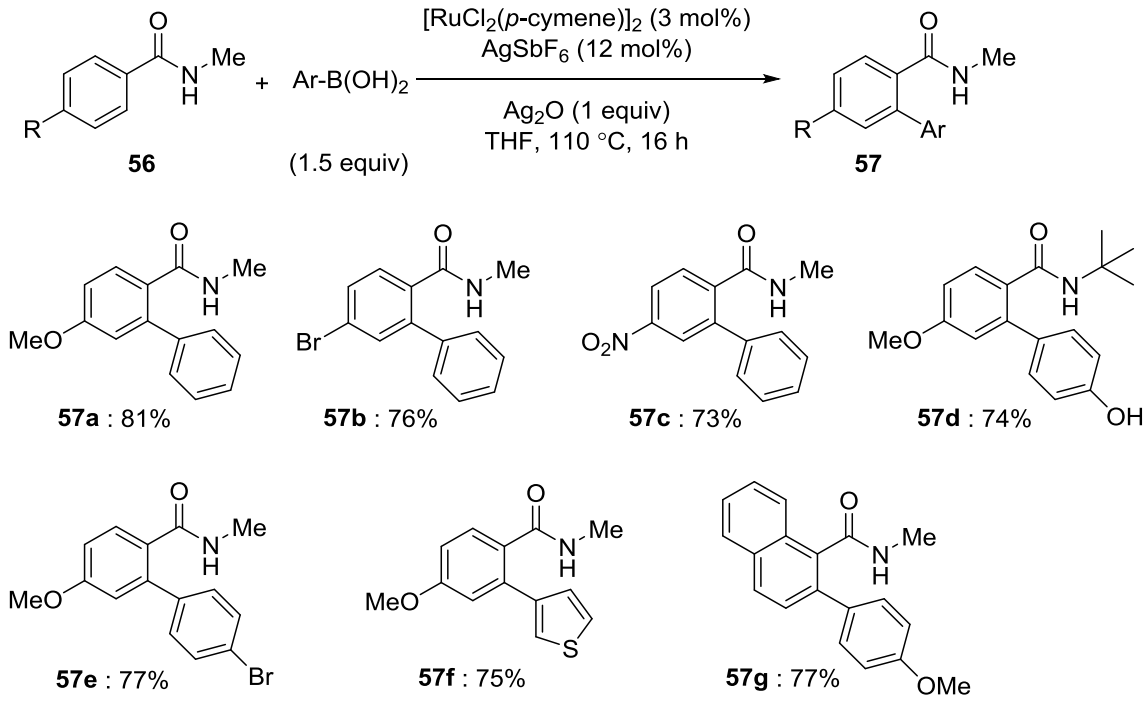


Scheme 17

1.1.4. Ru(0) catalysed *sp²* C-H catalysed arylation

Arylboronates can be used as a coupling partner with aromatic ketones to form *ortho*-arylated products, using $RuH_2(CO)(PPh_3)_3$ as the catalyst and pinacolone to suppress side reactions.[65-69] Also the product selectivity of mono- and diarylated products can be controlled by the use of styrene as an additive to suppress the formation of diarylation as previous work has shown that alkylation of aromatic ketones with styrene is much slower and only the monoalkylated products were isolated.[30]

In 2012, Jeganmohan and co-workers reported a direct *ortho*-arylation of *N*-alkylbenzamides with boronic acids.[70] 4-Methoxy-*N*-methylbenzamide was reacted with phenylboronic acid in the presence of 3 mol% of $[RuCl_2(p\text{-cymene})]_2$, 12 mol% of $AgSbF_6$, and 1 equivalent of of Ag_2O in THF at 110 °C for 16 hours to obtain the *ortho*-arylated product **57a** in 81% yield. The reaction has a broad substrate scope, and various functional handles were tolerated such as bromo, iodo, cyano and hydroxyl. A range of boronic acids were utilised in the reaction, both electron-donating and electron-withdrawing substituents were tolerated and afforded the arylated products in good yields, as well as heteroaromatics and alkenyl boronic acids (Scheme 18).

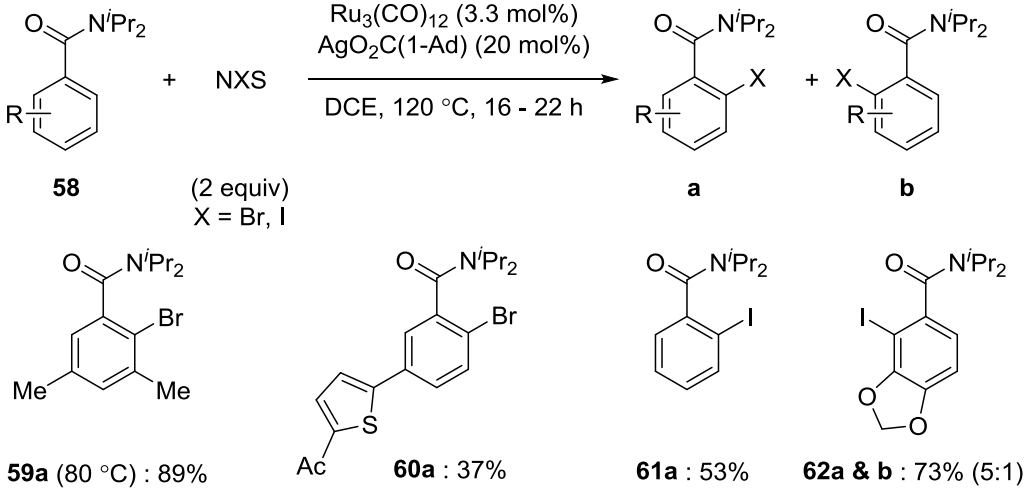


Scheme 18

The authors proposed that the first step of the mechanism involves the removal of the chloride from the Ru complex with $AgSbF_6$ providing the cationic ruthenium complex. Coordination of the carbonyl oxygen to the cationic ruthenium complex leads to *ortho*-metallation to give the cyclometallated intermediate. In the presence of Ag_2O, the boronic acid undergoes transmetallation followed by reductive elimination to provide the arylated product. The authors suggested that the Ag_2O has a dual role in the reaction, Ag_2O acts as a base for the boronic acid to accelerate the transmetallation step and also Ag^+ acts as a terminal oxidant to oxidise Ru(0) to Ru(II) for the regeneration of the active catalyst species. This chemistry was extended to acetanilides, but requires an additional additive $Cu(OTf)_2$ in the reaction.[71]

1.1.5. Ru(0) catalysed sp^2 C-H halogenation

Very recently, Ackermann and co-workers reported the first ruthenium-catalysed intermolecular C-H *ortho*–halogenation of arenes utilising NXS (*N*-halogensuccinimide) as electrophilic halogen sources (Scheme 19).[72] Bromination and iodination of various benzamides were achieved with high selectivity. The C-H bromination is accomplished in the presence of a Ru(0) catalyst $Ru_3(CO)_{12}$ and $AgO_2C(1\text{-Ad})$ and *N*-bromosuccinimide in DCE at 120 °C to obtain the *ortho*-brominated product in good yields and excellent regioselectivity.



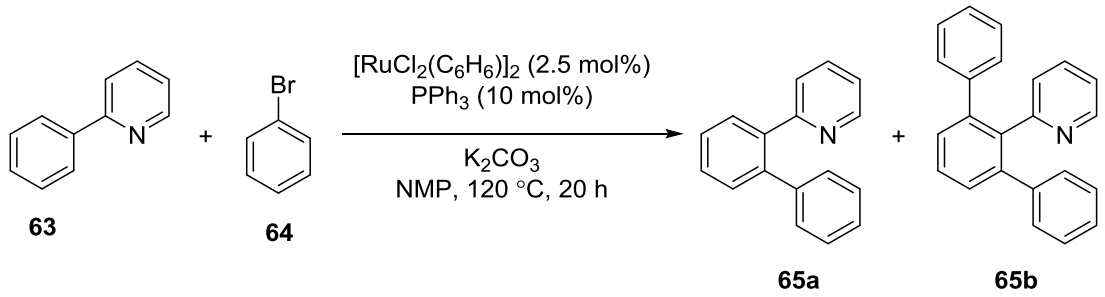
Scheme 19

1.2. Ru(II) catalysed *sp*^{2} C-H functionalisation

1.2.1. Ru(II) catalysed *sp*^{2} C-H arylation

Over the past decade, there have been numerous reports on ruthenium(II) catalysed *sp*^{2} C-H arylation and due to the extensive work in this area, herein, only selected examples of ruthenium(II) catalysed C-H arylations are described.[27]

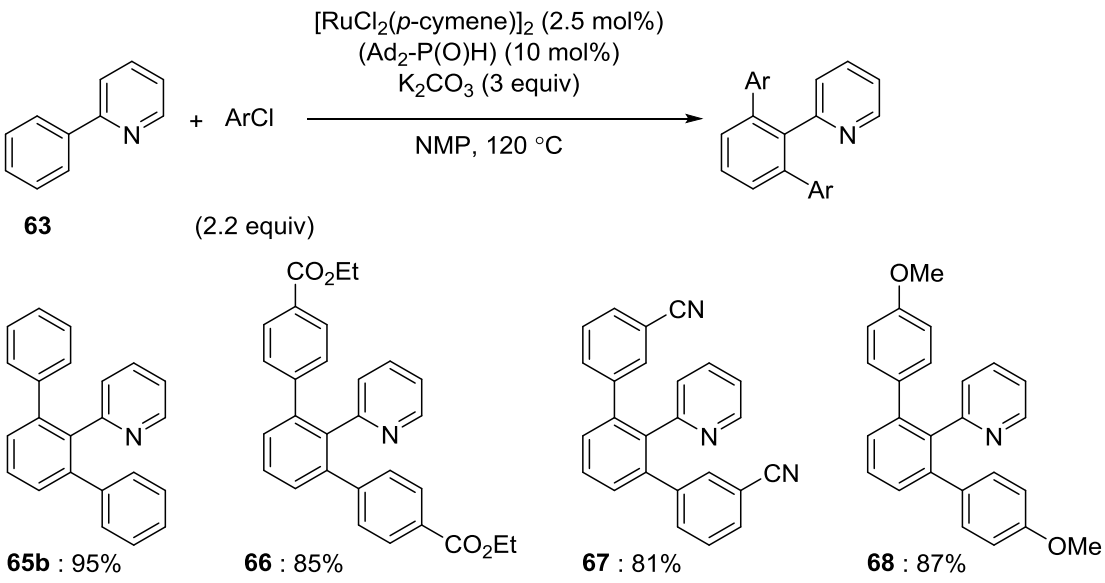
In 2001, pioneers of Ru(II) catalysed direct C-H arylation, Oi and Inoue reported the first efficient *ortho*-arylation of 2-phenylpyridne **63** with aryl halides using a Ru(II) catalyst.[73-78] The use of 2 – 2.5 mol% $[RuCl_2(C_6H_6)]_2$, in the presence of 10 mol% of PPh_3 and two equivalents of K_2CO_3 in NMP to afford the *ortho*-arylated product. The selectivity of mono- and diarylated products can be tuned by the equivalency of aryl bromide used. Equimolar amount of aryl bromide leads to monoarylation as the major products, whereas if the arylbromide is used in excess (3 equivalents); it leads to formation of diarylated products exclusively (Scheme 20). For direct *ortho*-arylation, both $RuCl_2(PPh_3)_3$ and $[RuCl_2(COD)]_2$ showed similar catalytic activity as $[RuCl_2(C_6H_6)]_2$. Other phosphine ligands, such as alkyl phosphines, phosphites and bidentate diphosphine were not as efficient as PPh_3. In terms of the arylating reagent, the reactivity was Br>I>OTf>Cl.



	65a	65b
PhBr (1 equiv)/ K_2CO_3 (2 equiv)	71%	11%
PhBr (3 equiv)/ K_2CO_3 (6 equiv)	0%	77%

Scheme 20

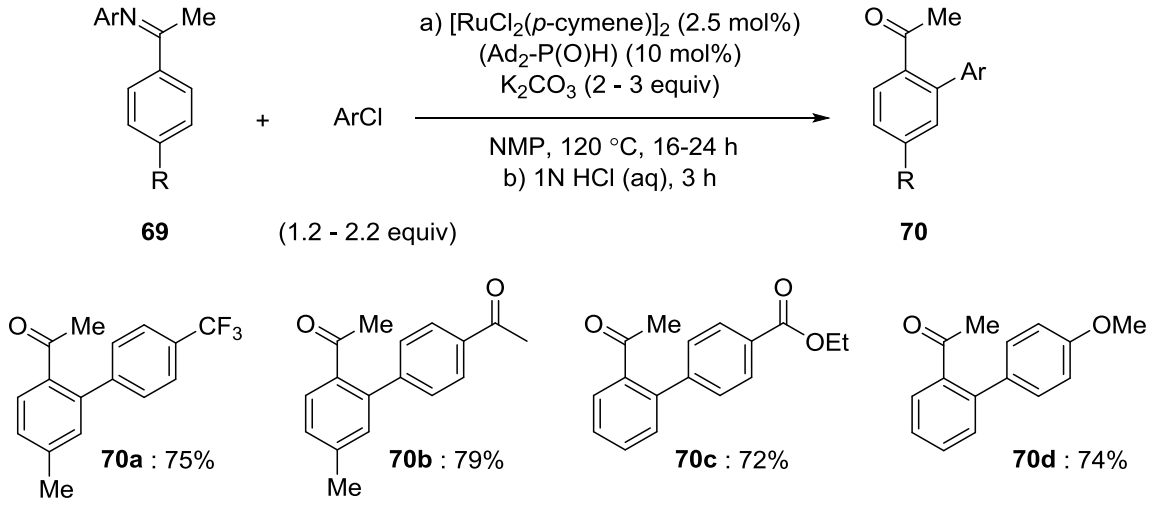
In 2005, Ackermann transformed the arylation of arenes using an alternative ligand to the traditional ligand, PPh_3.[79] Phosphine oxide $R_2P(O)H$ were shown to activate the Ru(II) catalyst more efficiently than phosphine ligands. The arylation is effective using readily available aryl chlorides as the coupling partner. The best preligand was $(adamantly)_2P(O)H$, ($Ad_2P(O)H$) (10 mol%) in the presence of $[RuCl_2(p\text{-cymene})]_2$ and base, K_2CO_3 in NMP at 120 °C for 5 hours and 2-phenylpyridine was successfully coupled with chlorobenzene in 95% yield. Various aryl chlorides were efficiently coupled to 2-phenylpyridine to afford the corresponding diarylated product (Scheme 21).



Scheme 21

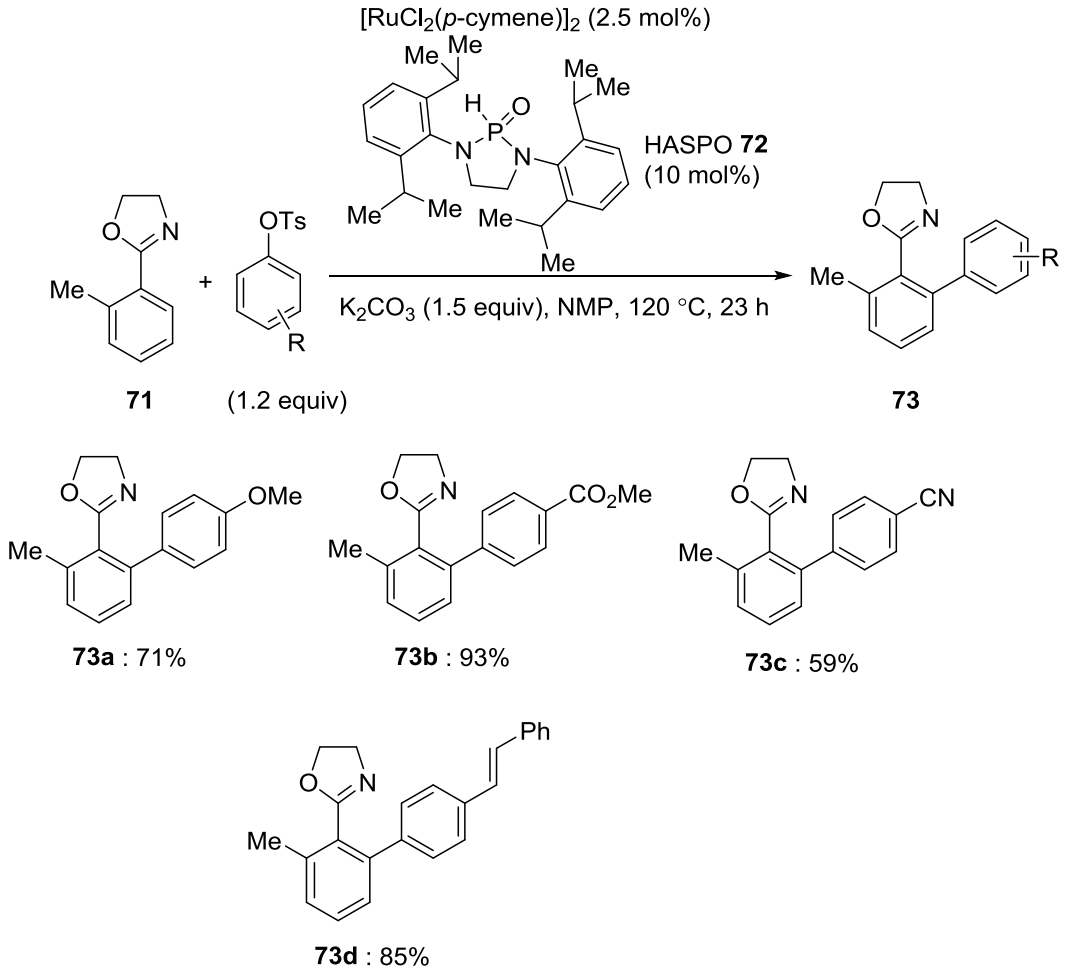
This catalytic system was utilised to monoarylate ketimines with aryl chlorides, the products were subsequently hydrolysed to give the corresponding ketones (Scheme 22). This catalytic system for monoarylation of ketimines is more efficient in comparison to Oi and Inoue's system;[74] here, the

reaction is selective, only the monoarylated product is formed. In addition it is more versatile, a wider range of aryl chlorides with various functional groups are tolerated. Furthermore, this catalytic reaction is air and moisture-stable, making it much easier to handle. The authors initially suggested $R_2P(O)H$ simply played the role of a preligand, and possibly form the anionic phosphorus bonded ligand. Later, work from Dixneuf established that C-H bond activation of Ru(II) occurs *via* a coordinated base-assisted C-H deprotonation mechanism.[80] Ackermann proposed that the role of $R_2P(O)H$ acts similarly to a carboxylate, in which the ligand coordinates to the Ru for deprotonation of sp^2 C-H bonds.



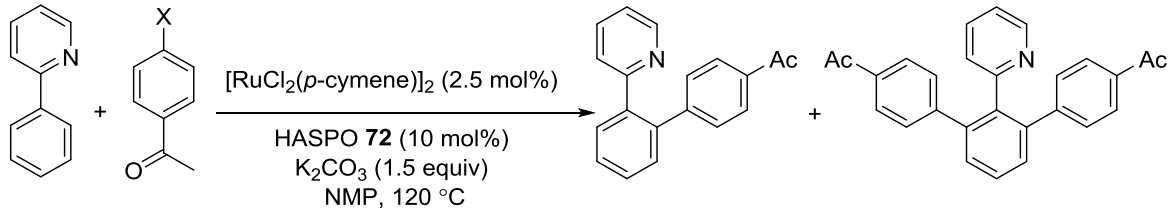
Scheme 22

When $[RuCl_2(p\text{-cymene})]_2$ is utilised with phosphine oxide (HASPO) **72**, the direct *ortho*-arylation of oxazoline **71** was achieved with aryl tosylates.[81] A number of functional groups were tolerated including alkene, nitrile, ester, ketone and trifluoromethyl groups (Scheme 23).



Scheme 23

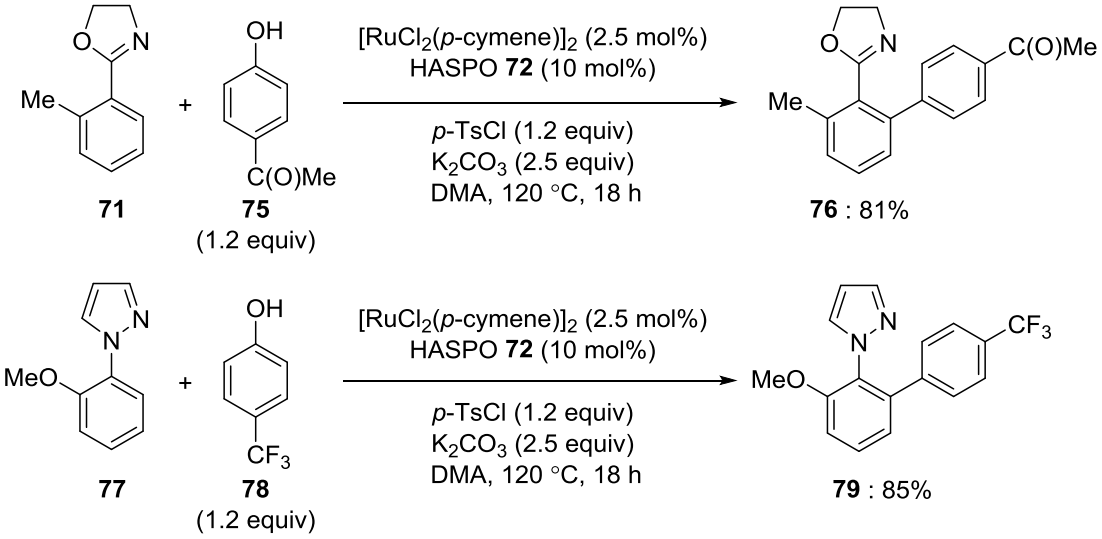
Interestingly, the selectivity of the product can be manipulated through the choice of electrophile. Aryl chlorides produce the diarylated product, whereas when aryl tosylates are employed, the monoarylated product is formed selectively in good yields (Scheme 24).



Scheme 24

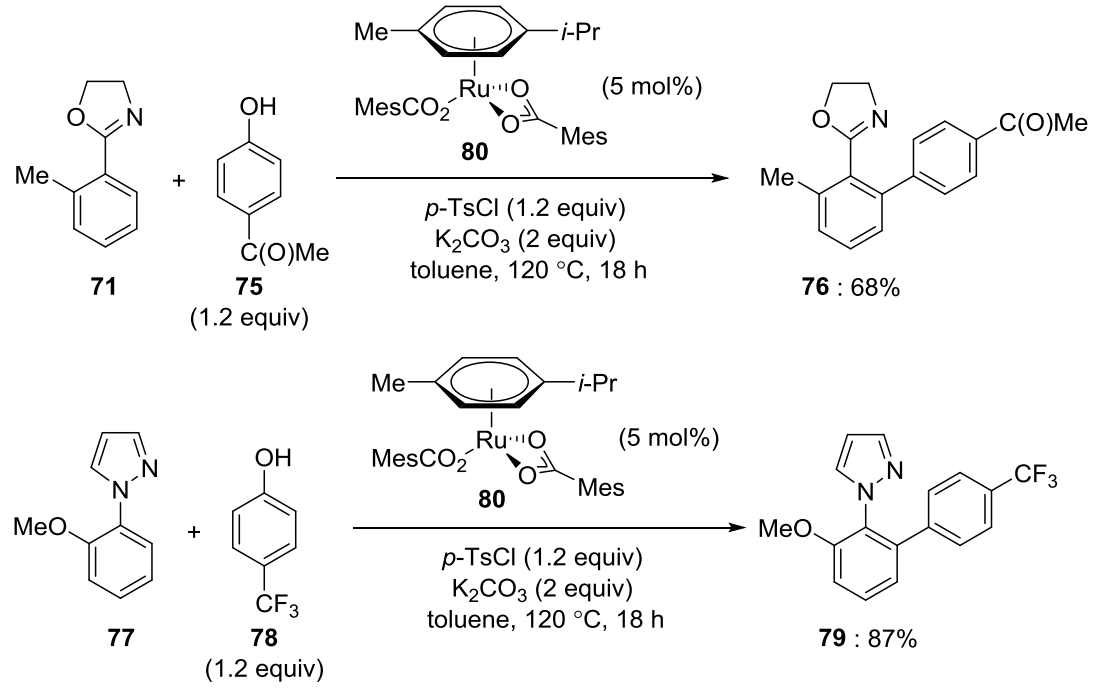
A one-pot method was developed utilising phenols as the coupling partner in the presence of *para*-toluenesulfonyl chloride (*p*-TsCl) with the catalytic system previously developed, allows for

in situ tosylate generation of C-C bond formation with wide functional group tolerance.[82] (Scheme 25)



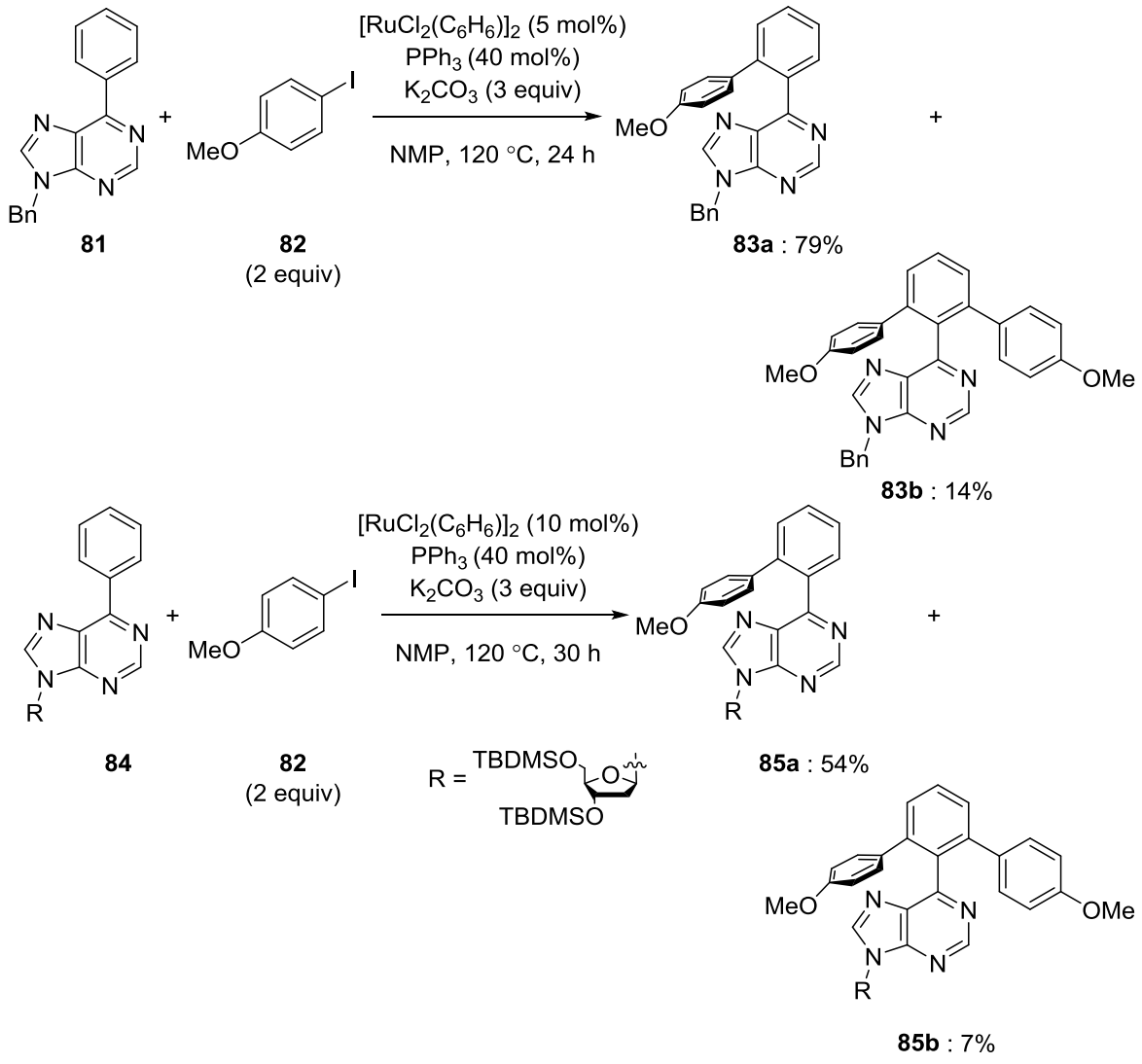
Scheme 25

The arylation of arenes by *in situ* generation of tosylates has been developed further by Ackermann and co-workers by switching the catalyst to a ruthenium biscarboxylate complex **80** the reaction was able to be performed in water.[83] Utilising 5 mol% of $[Ru(O_2CMes)_2(p\text{-cymene})]$ **80** along with *p*-TsCl in toluene at 100 °C for 18 hours afforded the *ortho*-arylated coupled product (Scheme 26).



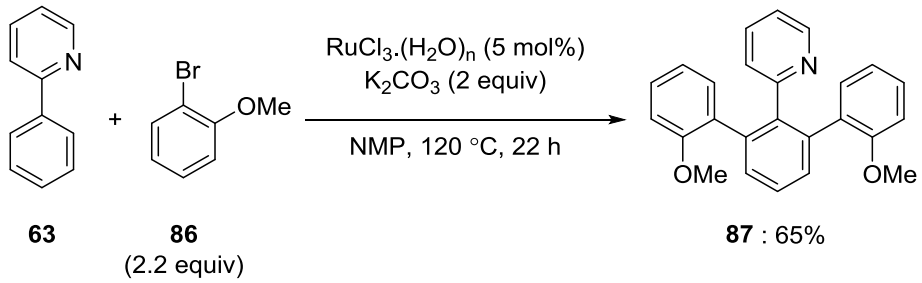
Scheme 26

In 2011, Lakshman and co-workers extended C-H arylation to biological compounds, utilising conditions developed by Oi and Inoue, a C-H *ortho*-arylation was performed on purine.[84] Despite the multiple nitrogen atoms present in purine **81**, the substrate was successfully arylated using aryl bromides or iodides in the presence of 5 mol% $[RuCl_2(C_6H_6)]_2$, 40 mol% PPh_3 and K_2CO_3 in NMP at 120 °C. Deoxyribonucleosides **84** were also suitable substrates however; a higher catalyst loading of 10 mol% was needed as well as a longer reaction time of 30 hours. In all cases, both mono- and diarylated products were formed, with monoarylated products as the predominant product (Scheme 27).



Scheme 27

Aryl bromides can also react under a phosphine free environment, with $RuCl_3(H_2O)_n$ formally a ruthenium(III) complex as the ruthenium source.[85] This system is compatible with pyridine, oxazoline and pyrazole. Even with sterically hindered electrophiles such as 2-bromo anisole **86**, the aryl bromide was able to couple in good yield (Scheme 28).

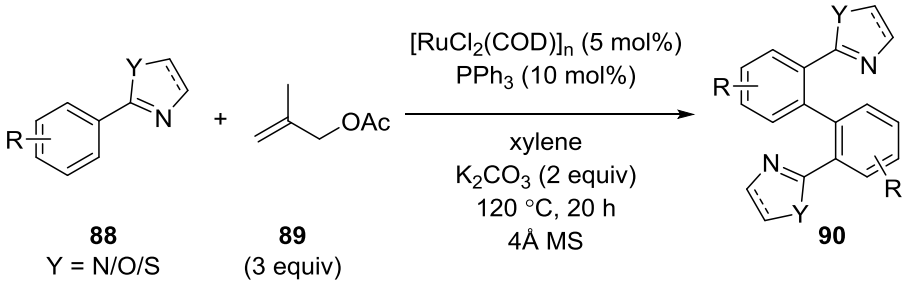


63 **86** (2.2 equiv) **87** : 65%

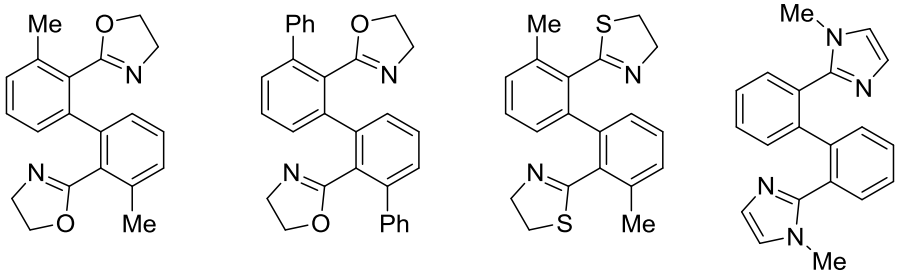
Scheme 28

1.2.2. Ru(II) catalysed sp^2 C-H dimerisation

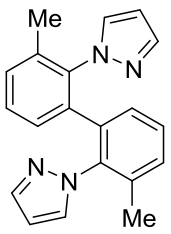
An *ortho*-selective homocoupling of 2-aryloxazoline and 2-arylimidazoles can be achieved with $[RuCl_2(COD)]_n$ (5 mol%) with 3 equivalents of allyl acetate **89** as a hydrogen scavenger (Scheme 29).



88 Y = N/O/S **89** (3 equiv) **90**



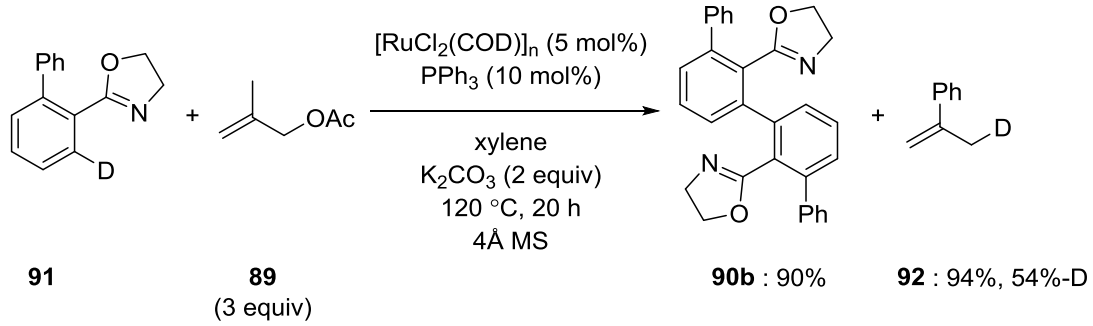
90a : 83% **90b** : 93% **90c** : 75% **90d** : 74%



90e : 41%

Scheme 29

Deuterated experiments were performed to gain insight into the reaction mechanism. *Ortho*-deuterated aryloxazoline **91** undergoes C-D bond cleavage as a result, a deuterium atom was incorporated into α-methyl styrene **92** (Scheme 30).



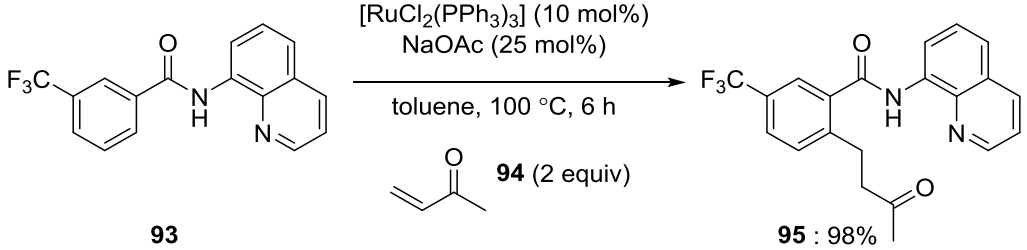
91 **89** (3 equiv) **90b** : 90% **92** : 94%, 54%-D

Scheme 30

Homocoupling reactions can also be performed on other substrates such as 2-arylpyridines, arylpyrazoles and aryl triazoles to afford the corresponding dimers as reported by Li and Ackermann respectively.[86, 87]

1.2.3. Ru(II) catalysed sp^2 C-H alkylation

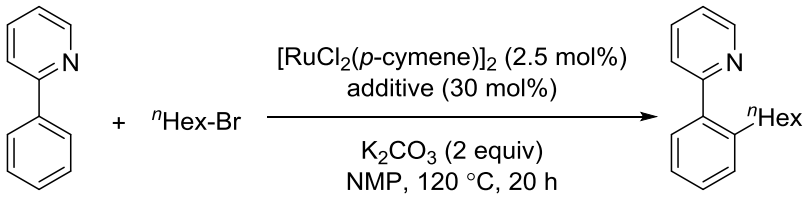
Ruthenium(0)-catalysed *ortho*-C-H alkylation of aromatic ketones with olefins has been studied extensively, as described previously. Further research has explored C-H alkylation using ruthenium(II) species to complement the previous ruthenium(0) work. Recently, Roquet and Chatani have reported a ruthenium(II)-catalysed *ortho* C-H alkylation of aromatic amides with various α,β-unsaturated ketones with a removable bidentate directing group, 8-aminoquinoline (Scheme 31).[88] Both electron-rich and electron-deficient amides were alkylated with a variety of alkyl and aryl enones. The major product is the *ortho*-monoalkylated amide, and in many cases, it was the sole product produced. However, there have been some cases where alkylation takes place predominantly on the sterically congested site. Conversely, in the case of a *meta*-fluoro substituent, the most substituted site is alkylated, however this was not observed for *meta*-methoxy derivative, which is also an effective coordinating group.



93 **95** : 98%

Scheme 31

Alternatively, C-H alkylated products can be obtained by using an alkyl halide as the electrophile. In 2009 Ackermann, reported the first ruthenium(II) catalysed direct *ortho* C-H alkylation of arenes with unactivated alkyl halides bearing β-hydrogen atoms.[89] The use of phosphine ligands such as PPh_3 and PCy_3 gave poor yields, however, catalytic amounts of carboxylate ligands provided higher yields and 1-$AdCO_2H$ was found to give the best catalyst turnover of 69% yield (Scheme 32).

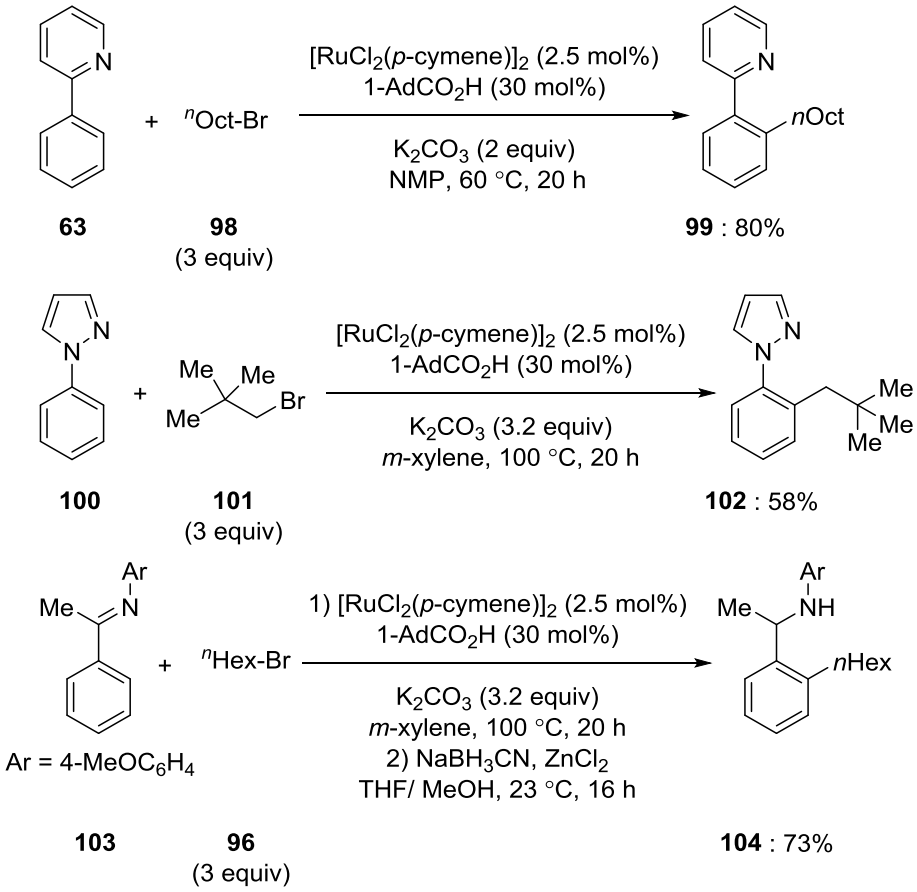


63 **96** (3 equiv) **97**

additives
PPh_3 : 21%
PCy_3 : 23%
$MesCO_2H$: 33%
$^n PrCO_2H$: 53%
$^i PrCO_2H$: 61%
1-$AdCO_2H$: 69%

Scheme 32

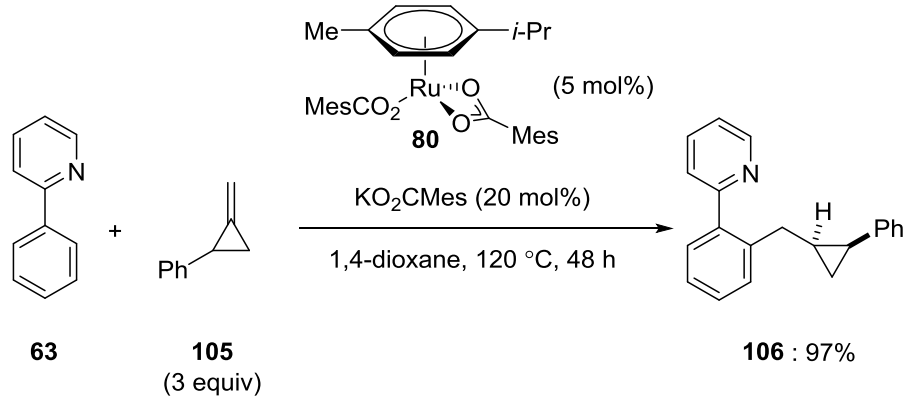
Alkylation was performed on 2-phenylpyridine, 1-phenylpyrazole and ketimine derivatives with primary and secondary alkyl substituents, as well as sterically hindered cyclopentyl bromide and neopently bromide derivatives. In order to ascertain the reaction mechanism alkylation with an alkene under identical reaction conditions was attempted. Only trace amounts of alkylated products were detected, it can be deduced for this experiment that the reaction mechanism does not involve a β-hydride elimination and subsequent hydroarylation route (Scheme 33).



Scheme 33

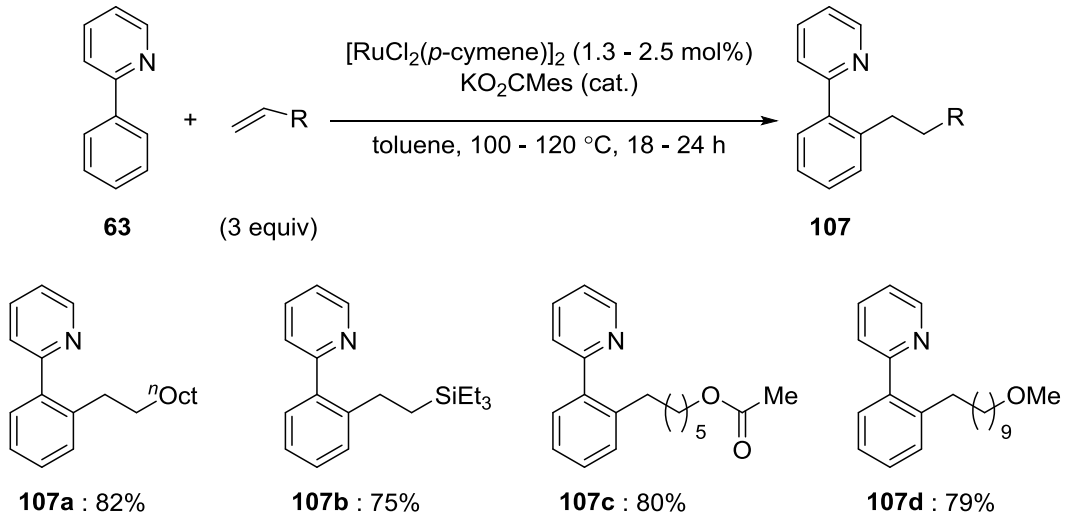
Another method of obtaining C-H alkylated products is *via* hydroalkylation. For the past few years, Ackermann's group has been reporting hydroalkylations of phenylpyridine with methylene cyclopropanes *via* C-H functionalisation.[90, 91] One method utilises $[RuCl_2(COD)]_n$ with XPhos , as the catalyst system in 1,4-dioxane at 120 °C for 48 hours.[90] In most cases the anti-Markovnikov addition product is formed, however, there were also some side products formed by Diels-Alder cycloaddition and self-reorganisation products were obtained as well.

Recently, Ackermann's group has demonstrated hydroalkylation using the well-defined ruthenium complex $[Ru(MesCO_2)_2(p\text{-cymene})]$ **80** plus the additive KO_2CMes in either 1,4-dioxane or toluene as the reaction medium at 120 °C for 48 hours.[91] This method is superior to the method reported previously as the present methodology provides a more efficient transformation, because it does not form any undesired products in the reaction. The authors proposed that the carboxylate ligand improves the chemoselectivity of the catalyst, in which it favours the desired anti-Markovnikov *trans*-hydroalkylation products (Scheme 34).



Scheme 34

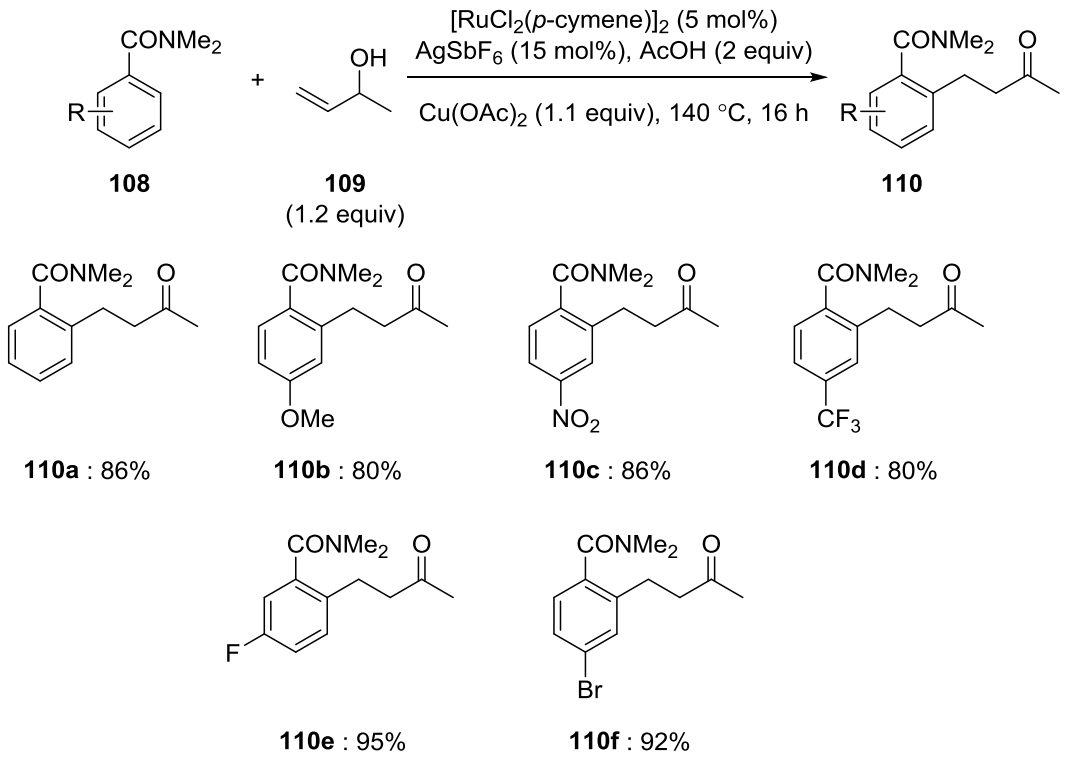
Ackermann and co-workers have also reported the hydroalkylation using unactivated alkenes *via* the *in situ* generated ruthenium(II) biscarboxylate catalyst system.[92] 2-Phenylpyridine underwent hydroalkylation with unactivated alkene in the presence of $[RuCl_2(p\text{-cymene})]_2$ and catalytic amount of KO_2CMes in toluene at 100 – 120 °C for 18 – 24 hours (Scheme 35). Other directing groups were compatible in the reaction including, pyrazolyl, pyrimidyl and imidazoyl groups. The catalytic system was tolerant to various functional groups such as ether, ketone, hydroxyl or ester substitutents and furnished the hydroarylated products in high yields.



Scheme 35

In a separate study, Jiang and co-workers described the oxidative alkylation of aryl amides with allylic alcohols (Scheme 36).[93] The reaction has a broad substrate scope, and both electron-donating and electron-withdrawing groups such as methoxy, fluoro, bromo, cyano, nitro and

trifluoromethyl are all compatible in the reaction. However, this reaction is limited to but-3-en-2-ol **109** only, as other allylic alcohols were not explored.



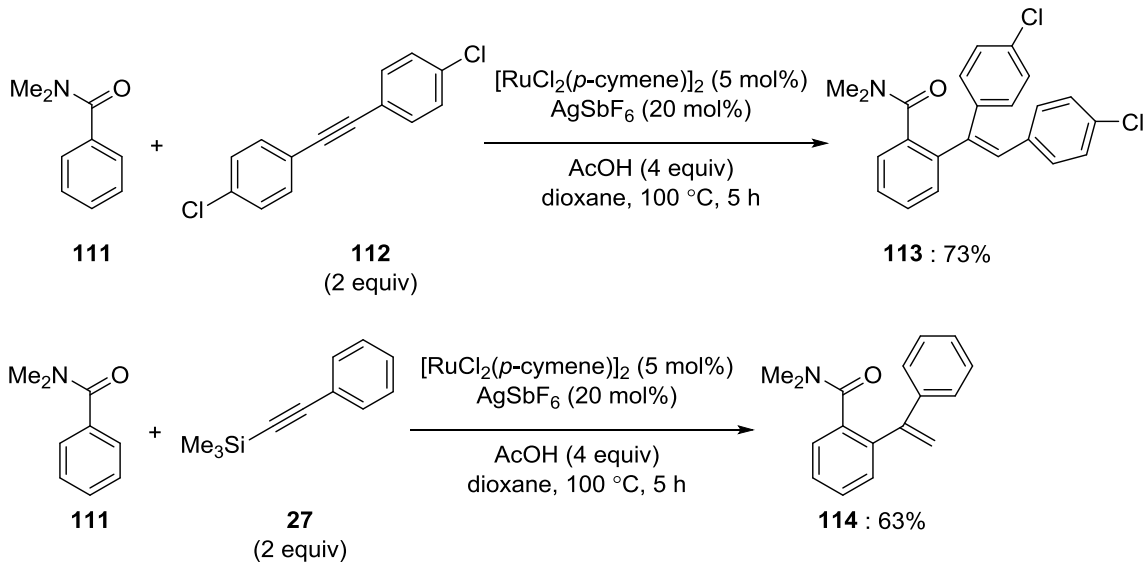
Scheme 36

1.2.4. Ru(II) catalysed sp^2 C-H alkenylation and allylation

As mentioned previously, the first example of ruthenium(0)-catalysed alkenylation was reported by Murai in 1995. Since then there has been significant research focussed on sp^2 C-H alkenylation.[94] There are various types of C-H alkenylation, the most common protocol for alkenylation is *via* catalytic addition of alkynes to C-H bonds.

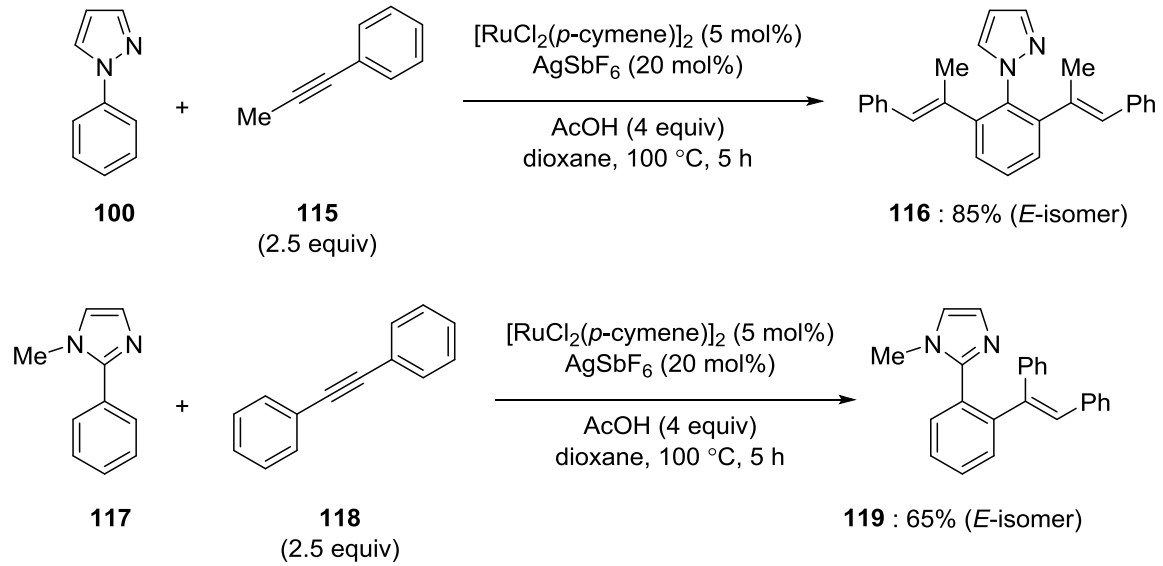
A recent example of C-H alkenylation was reported by Miura *et al*., in this study the researchers utilised alkynes as the coupling partner with benzamides. The reaction furnishes alkenes with high regio- and stereoselectivity to provide the *ortho*-alkenylated product.[95, 96] The reaction requires stoichiometric amount of AcOH, as decreasing the amount of AcOH to 10 mol%, reduced the yield dramatically. Furthermore replacing AcOH with other acids did not improve the reaction efficieny, as no base is used in the reaction, it seems AcOH is acting as the ligand for the C-H metallation

step. Reaction of benzamide with various alkynes proceeds smoothly to produce the desired products in moderate to good yields. The reaction of benzamide **111** and 1-phenyl-2-(trimethylsilyl)acetylene **27** proceeds efficiently but it underwent desilylation to produce the 1,1-diarylethene **114** in 63% yield (Scheme 37).



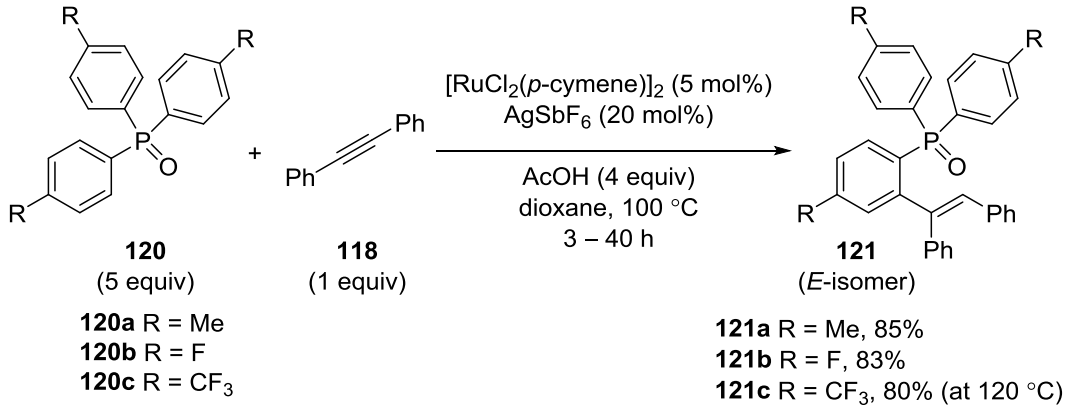
Scheme 37

In addition to benzamide the catalytic system was found to be suitable with pyrazoles and imidazoles as a directing group. Treatment of phenylpyrazole with alkyne **115**, underwent 2-dialkenylation as the major product **116**. Under similar conditions, 2-phenylimidazole also provided the dialkenylated product selectively. In contrast, 1-methyl-2-phenylimidazole provided the mono-alkenylated product selectively as the sole product **119** (Scheme 38).



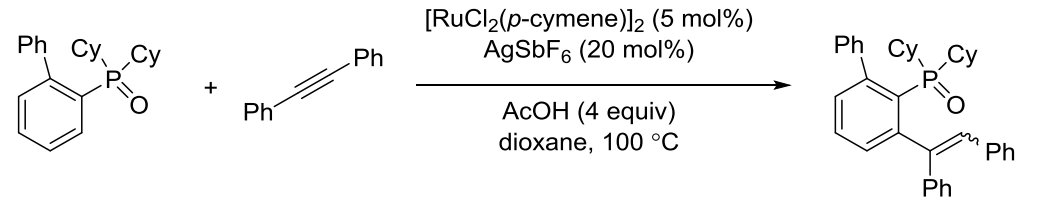
Scheme 38

Aryl phosphine oxides **120** have been employed as substrates for *ortho*-alkenylation *via* alkyne insertion in the presence of a ruthenium(II) catalyst. $[RuCl_2(p\text{-cymene})]_2$, with $AgSbF_6$ and AcOH as additives in dioxane at 100 °C, produced the *ortho*-alkenylphenylphosphine oxides with complete control of regio- and stereoselectivity.[97] Electron-donating and electron-withdrawing substituents on the aryl ring of phosphine oxide were tolerated in the reaction. Triarylphosphine oxides containing CF_3 **120c** performed relatively sluggishly in comparison with other functional groups (Scheme 39).



Scheme 39

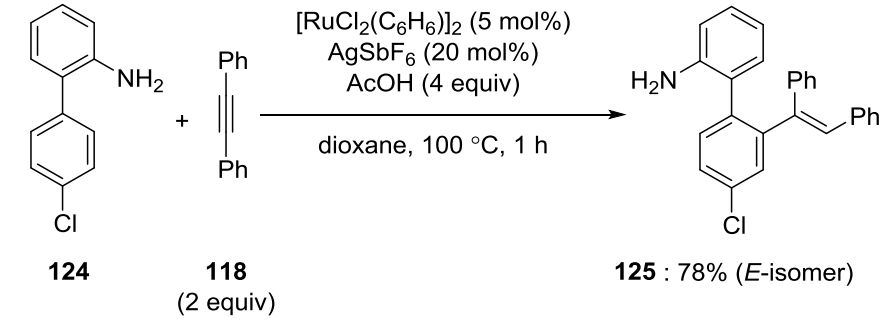
Oxides of conventional phosphine ligands such as Cy JohnPhos **122** can also undergo alkenylation, in high yield; however, the product **123** was formed as a mixture of *E*/*Z* isomers (Scheme 40). Unfortunately, the reaction is limited to internal alkynes only, as terminal alkynes are unreactive.



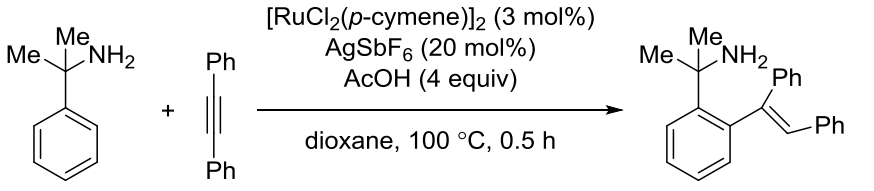
122 (5 equiv) **118** (1 equiv) **123** : 98%, *E/Z* = 84:16

Scheme 40

Amines can also be used as a directing group for C-H functionalisation as demonstrated by Miura *et al*., treatment of 2-aminobiphenyls such as **124** with alkynes in the presence of $[RuCl_2(C_6H_6)]_2$, $AgSbF_6$ and AcOH in dioxane produced the *ortho*-alkenylated product **125** regioselectively in moderate to good yields.[98] By changing the catalyst to $[RuCl_2(p\text{-cymene})]_2$ utilising the same reaction conditions, this method can be applied to cumylamine **126** to afford the *ortho*-alkenylated product **127** (Scheme 41). Mechanistic studies of deuterated d_5-2-aminobiphenyl revealed that deuterium exchange took place on both product and starting material, which indicates the C-H metallation step is reversible.



124 **118** (2 equiv) **125** : 78% (*E*-isomer)

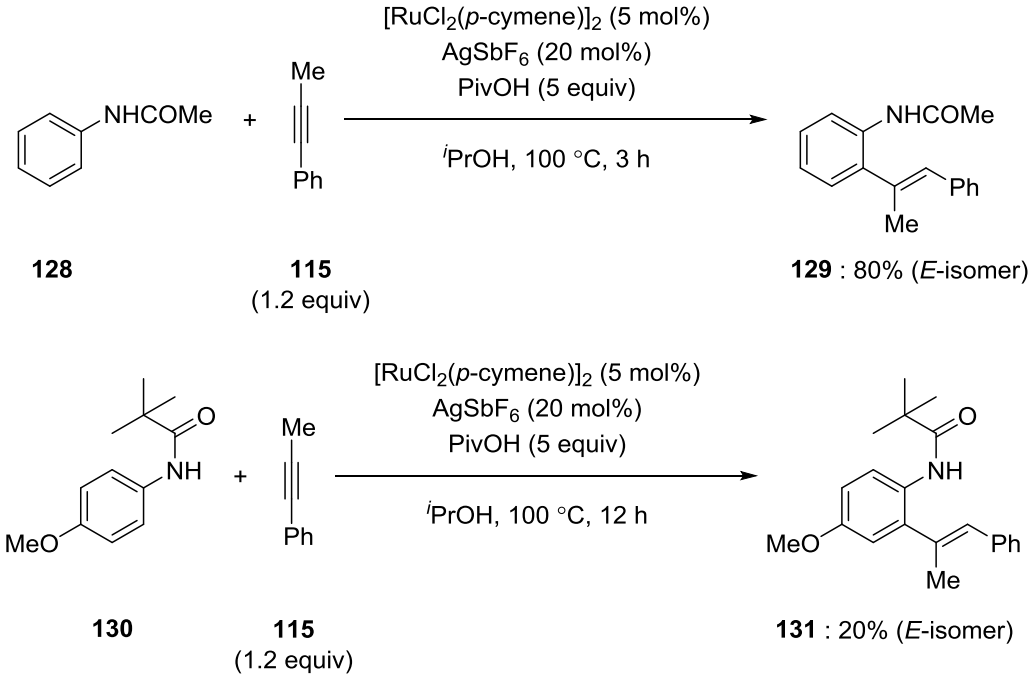


126 (1 equiv) **118** (1 equiv) **127** : 67% (*E*-isomer)

Scheme 41

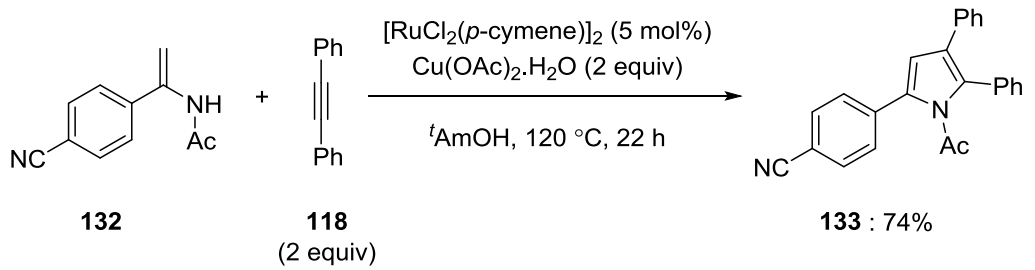
Jeganmohan and co-workers have recently reported an efficient method for synthesising *ortho*-alkenylated anilines with Ru catalysis in two steps.[99] Acetanilide **128** is used as the masked amine

to couple with alkynes in the presence of $[RuCl_2(p\text{-cymene})]_2$, pivalic acid and $AgSbF_6$ in ^{i}PrOH at 100 °C for 12 hours, leads to the formation of *ortho*-alkenylated acetanilides in good yields. Both symmetrical and unsymmetrical alkynes are applicable in the reaction and gave the desired products with total regiocontrol. When 4-methoxypivalamide **130** was subjected to the hydroarylation reaction conditions the alkenylated product **131** was obtained in 20% yield, this drop in yield is due to the bulky pivalate group hindering the metal centre from coordinating to the carbonyl oxygen to enable cyclometallation to take place (Scheme 42).



Scheme 42

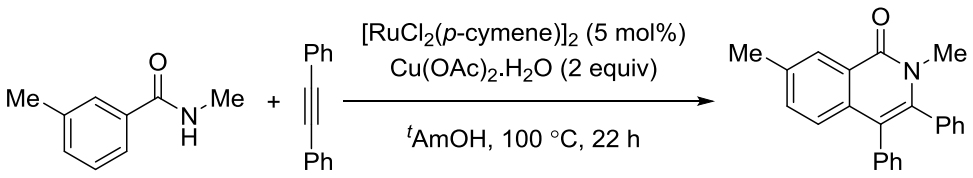
Insertion of alkynes can also lead to annulation to provide easy access to a diverse range of heterocycles.[100] A versatile pyrrole synthesis through ruthenium-catalysed C-H functionalisation of enamines has been demonstrated (Scheme 43).[101] Numerous functional groups were tolerated, including ester, vinyl, bromo, cyano and nitro substituents. In addition, heteroaromatic enamines such as pyridine and thiophene moieties furnished the corresponding desired pyrroles in good yields.



Scheme 43

To understand the mechanism of this protocol, mechanistic experiments of the oxidative annulation in isotopically labelled solvent d_4-MeOH were performed. In the absence of an alkyne, the enamine undergoes H/D exchange under the standard conditions, which suggests the C-H bond activation on enamines to be reversible in nature. However, in the presence of the alkyne, the H/D scrambling was not observed. The authors rationalised the mechanism as an alkyne-coordinated ruthenium complex undergoing an irreversible C-H bond metallation.

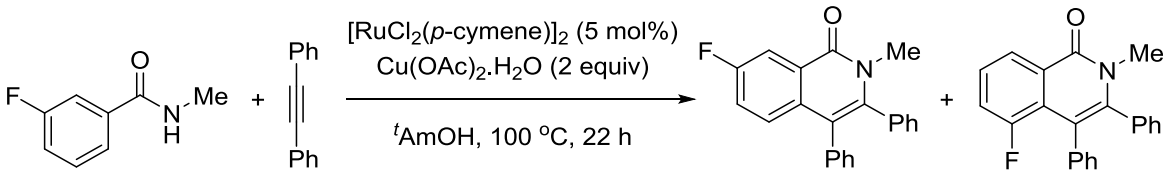
In 2011, Ackermann and co-workers reported the first ruthenium-catalysed oxidative annulation reaction of alkynes with benzamides, to produce isoquinolones (Scheme 44).[102] The reaction is highly chemo- and regioselective. The catalyst system is tolerant to various functional groups, such as fluoro, chloro, or ester substituents. *N*-benzamides with various *N*-protecting groups including *N*-alkyl, *N*-benzyl or *N*-aryl derivatives were efficiently converted to the corresponding isoquinolone, however only internal alkynes are suitable in the reaction.



134 **118** **135** : 81%

Scheme 44

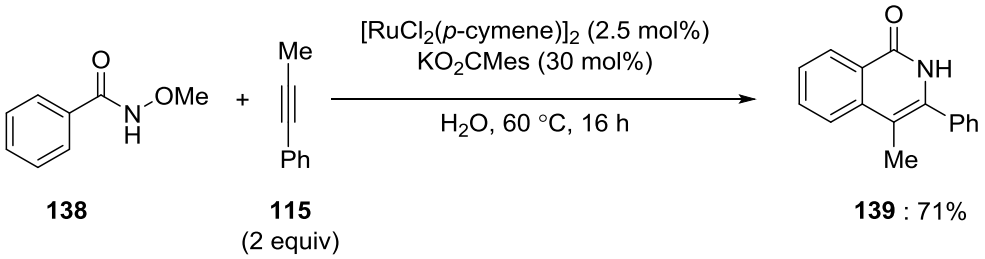
Intramolecular competition experiments with *meta*-substituted substrates were showed to be controlled by steric interactions. Interestingly, the presence of an electronegative heteroatom on the *meta*-position gave significant amounts of the regioisomer **137b** where the C-H functionalisation takes place at the 2-position of the arene as well as the desired product **137a** (Scheme 45). These observations can be due to the acidity of the C-H bonds or Ru-C stability.



136 **118** **137a** : 17% **137b** : 66%

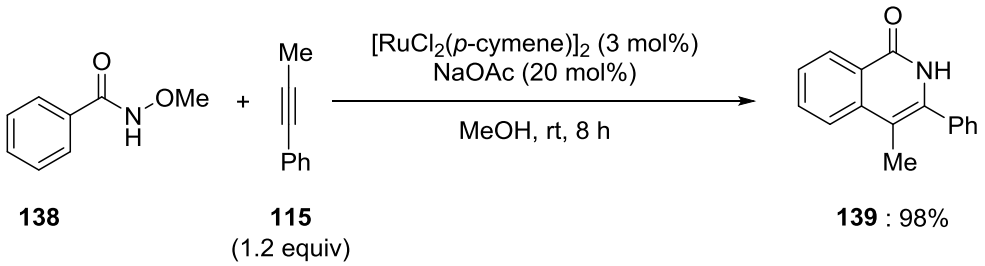
Scheme 45

Ackermann and co-workers then devised a more sustainable method for synthesising isoquinolone derivatives utilising water as the reaction medium.[103] *N*-methoxybenzamides **138** are employed as the substrate for annulations of alkynes. The *in situ* generated catalytic system was applicable to both electron rich and electron deficient derivatives tolerating functional groups that included nitro, fluoro and chloro substituents. In addition, aryl as well as alkyl alkynes were compatible in the reaction, and unsymmetrical alkynes provided the desired products with high regioselectivities (Scheme 46).



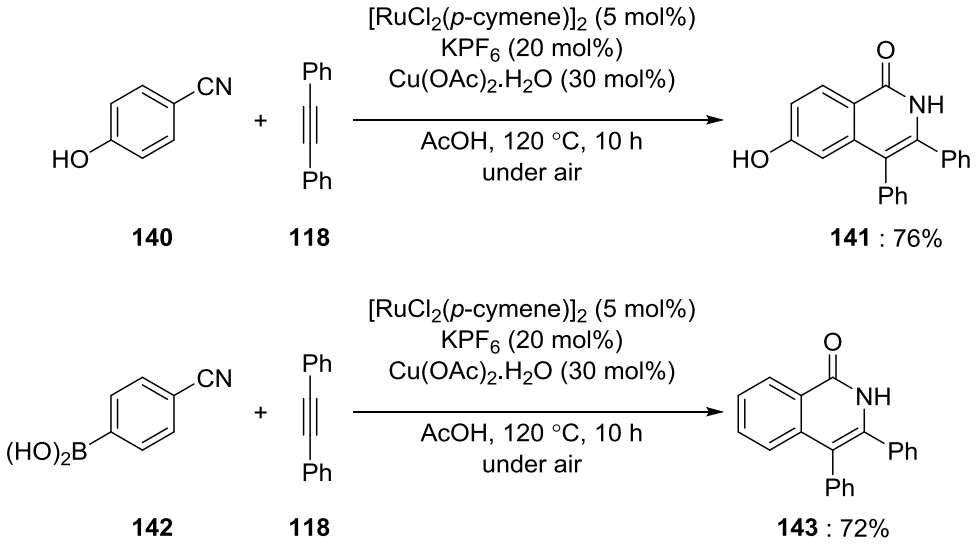
Scheme 46

Li and co-workers developed a mild reaction for the synthesis of isobenzoquinolones using Ru catalysis (Scheme 47).[104] Various substituted benzamides were treated with an alkyne and gave the corresponding isoquinolone derivatives in high yields. The reaction has a broad substrate scope, both electron-rich and electron-poor *N*-methoxybenzamides participated well in the reaction. Even heteroaromatic benzamides were suitable in the reaction albeit the lower efficiency compared to other substrates. In contrast with the study by Ackermann, the present reaction is a lot milder, as the reaction is performed at room temperature with a shorter reaction time and higher yields.



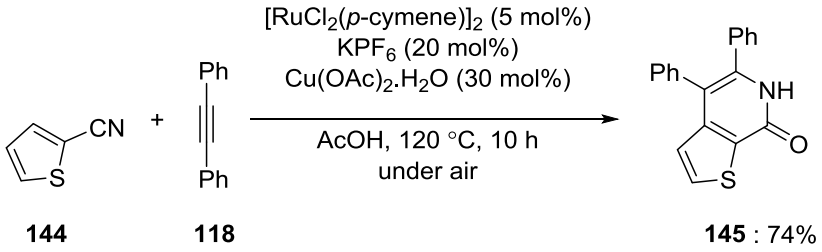
Scheme 47

Alternatively, isoquinolones can be synthesised with treatment of aromatic nitriles with alkynes.[105] In the presence of $[RuCl_2(p\text{-cymene})]_2$, $Cu(OAc)_2.H_2O$ and KPF_6 in acetic acid at 120 °C for 10 hours the isoquinolone derivatives are formed in good yields. A wide range of functional groups are tolerated in the reaction, including unprotected alcohols, halogens, amino, carbonyl derivatives and nitro groups. Reaction in the presence of a boronic acid moiety **142** gave the protodeborylation product **143** in 72% yield (Scheme 48).



Scheme 48

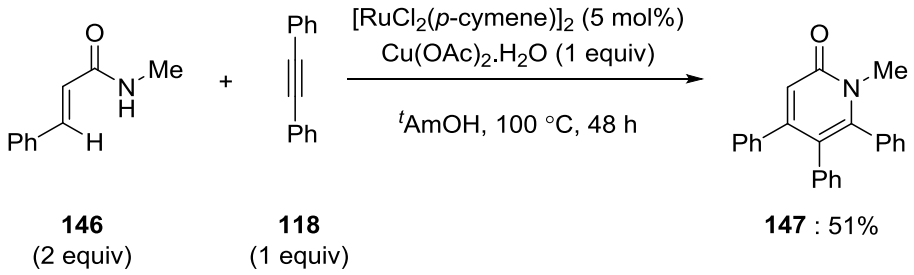
Heteroaromatic nitriles were also suitable substrates to undergo oxidative cyclisation to provide the isoquinolone product (Scheme 49). As the previous examples mentioned above, only the internal alkynes were applicable in the annulation.



Scheme 49

Ruthenium-catalysis can also be used for oxidative annulations of alkynes with acrylamides for the preparation of 2-pyridones as reported by Ackermann and co-workers.[106] Acrylamides bearing different substituents in the α- or β-position could be employed in the reaction. This reaction is

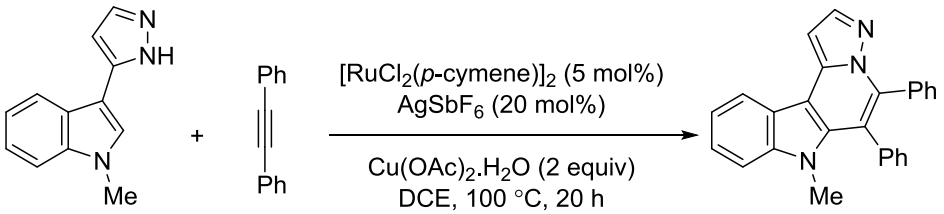
more efficient than the rhodium-catalysed oxidative coupling. For example when β-phenyl substituted acrylamide **146** was utilised under Rh catalysis no products were detected, however with Ru the pyridone product **147** was afforded in 51% yield (Scheme 50).[107]



146 (2 equiv) **118** (1 equiv) **147** : 51%

Scheme 50

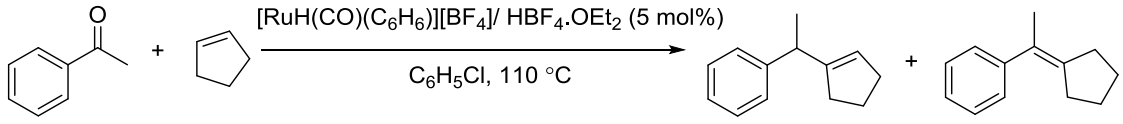
Other substrates have been explored for ruthenium-catalysed annulations such as 1-*H* pyrazole which reacts with alkynes *via* C-H/ N-H functionalisation.[108] The reaction did not require inert reaction conditions, which makes it easy to handle. The catalyst system was tolerant of various functional groups, such as nitro, chloro, cyano or amino substituents. Furthermore, the reaction can be used to synthesise bioactive-like indole structures **149** (Scheme 51). It is noteworthy that attempts to activate heteroaryl C-H bonds with a rhodium catalyst resulted in a poor yield.



148 **118** (2 equiv) **149** : 58%

Scheme 51

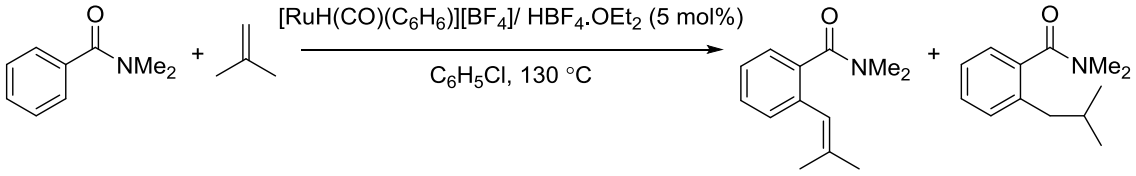
Yi and Lee have described the use of ruthenium(II) complex $[RuH(CO)(PCy_3)(C_6H_6)][BF_4]$ with $HBF_4.OEt_2$ to catalyse the intermolecular dehydrative coupling reaction of aromatic ketones with cyclic alkenes to give a 1:1 mixture of two alkene isomers. [109, 110] It is noteworthy that no reactive reagents are employed to activate the alkene in this reaction (Scheme 52). Sterically demanding alkenes such as cyclooctene and methylcyclopentene as well as trisubstituted olefins gave the corresponding products in poor yields.



150 **151** (2 equiv) **152a** & **152b** : 52%, (1:1)

Scheme 52

This catalytic system was also adopted for the coupling of aryl amides and unactivated alkenes to afford predominantly the oxidative alkenylated product (Scheme 53).[111] A small amount of the hydrogenated product was also formed. Various alkenes including cyclic alkenes and terminal alkenes were compatible in the reaction. The reaction can be carried out at a lower temperature of 80 °C for cyclic alkenes, but for terminal olefins, the reaction has to be performed at 150 °C. Reaction of aryl amides with 1,1-disubstituted terminal alkenes provided the *ortho*-C-H inserted product preferentially.



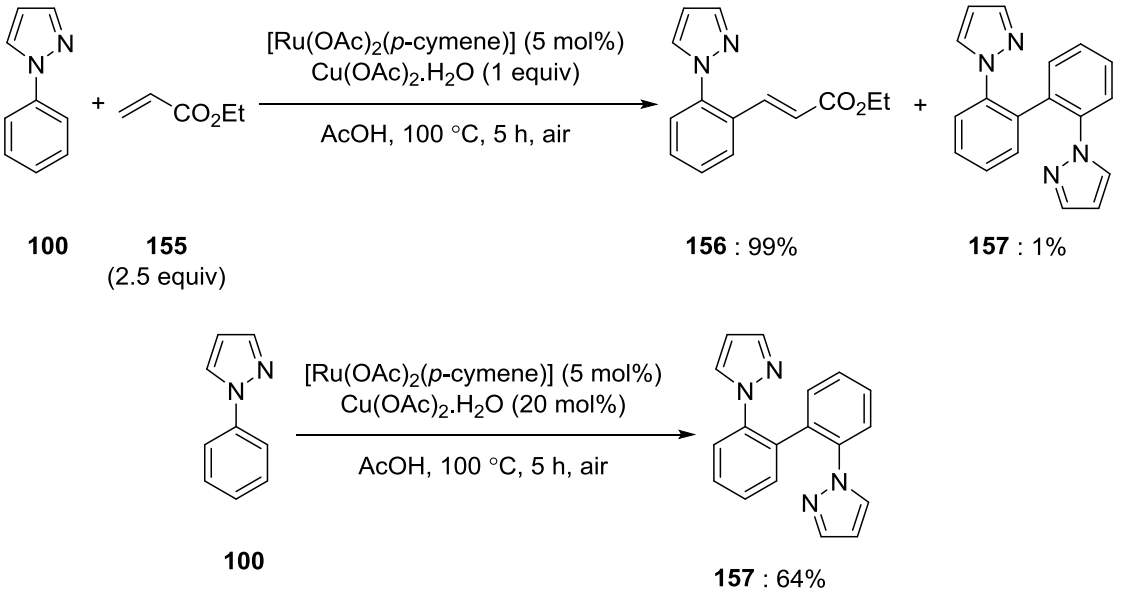
111 **153** (5 equiv) **154a** & **154b** : 84%, (40:60)

Scheme 53

The authors proposed the initial step involves arene exchange/π-coordination of the aryl amide/ketone to the Ru-H species which undergoes cyclometallation, followed by insertion of the alkene into the C-Ru bond and either β-elimination or oxidative addition to give the oxidative coupling product.

Arylation *via* C-H functionalisation can be obtained by direct oxidative alkenylations of arenes through two-fold C-H functionalisation. There are some examples of oxidative alkenylation by styrene derivatives. In 2011, Dixneuf and co-workers reported utilising [$Ru(OAc)_2$(*p*-cymene)] as the catalyst for the direct dehydrogenative alkenylation of *N*-pyrazoles with an olefin in the presence of additives $Cu(OAc)_2.H_2O$ in air and AcOH as the solvent at 100 °C for 5 hours.[112] The reaction formed the desired product **156** as well as a certain amount of homocoupled product **157**. In the absence of styrene, the homocoupled product **157** was made exclusively and isolated

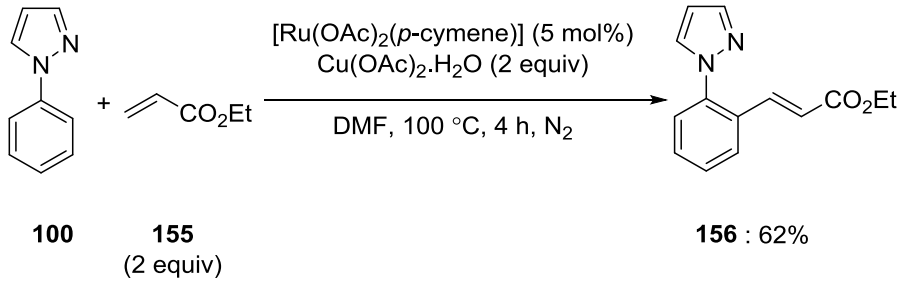
in 64% yield, whereas increasing the amount of styrene suppresses the formation of the by-product (Scheme 54).



Scheme 54

A variety of functionalised alkenes is suitable in the reaction, and less reactive acrylates such as methyl-, ethyl-, and benzylacrylates reacted sluggishly even with an extended reaction time of 30 hours, which consequently led to a high proportion of the homocoupled product. It was found that using stoichiometric amounts of $Cu(OAc)_2.H_2O$ is essential to ensure full conversion of the desired *ortho*-alkenylated product. Electronics on the substrate also have an impact of the stereoselectivity of the products. Phenylpyrazoles with electron-donating substituents such as methoxy and methyl groups were found to be more susceptible of dialkenylation, and formed both the mono and dialkenylated products in the reactions, whereas the electron deficient aryl pyrazoles gave the monoalkenylated product as the major product.

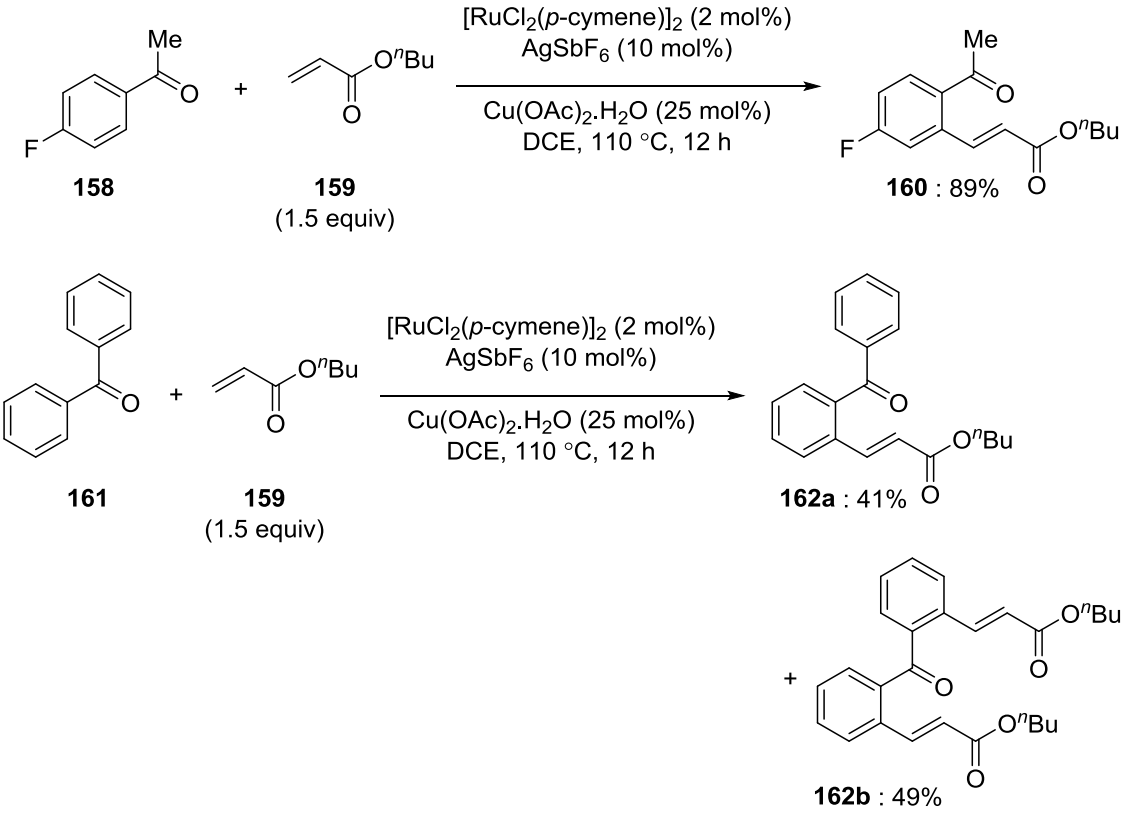
Miura *et al.* have also reported oxidative alkenylation of 1-phenyl pyrazole derivatives.[113] Despite the fact that Miura's conditions require an excess amount of oxidant $Cu(OAc)_2.H_2O$, this was compensated with a shorter reaction time and gave no homocoupled products (Scheme 55).



100 **155** (2 equiv) **156** : 62%

Scheme 55

Weak coordinating groups such as ketones, esters and carbamates have also been shown to be viable substrates for oxidative alkenylation. Various aromatic ketones reacted with olefins to provide the Heck-type products as demonstrated by Jeganmohan and co-workers.[114] Various substituted acetophenones bearing different functional groups reacted with *n*-butyl acrylate **159** and proceeded smoothly providing the *ortho*-alkenylated product in good yields and high regioselectivity. Only the mono-alkenylated products were observed (Scheme 56). However, in the case of bulkier benzophenone **161**, it provided a mixture of mono- **162a** and **162b** di-alkenylated products in 41% and 49% yields respectively.



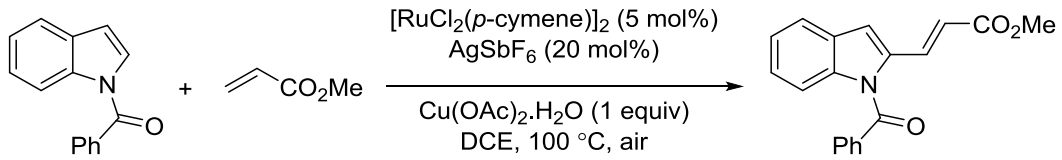
158 **159** (1.5 equiv) **160** : 89%

161 **159** (1.5 equiv) **162a** : 41%

162b : 49%

Scheme 56

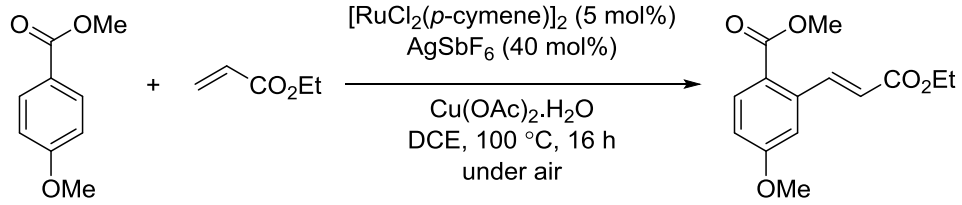
Alkenylation of indole at the C-2 position is difficult to achieve but by utilising the carbonyl oxygen as a directing group to promote alkenylation selectively on the C-2 position of indoles under ruthenium catalysis.[115] *N*-benzoylindole **163** reacts with acrylates in the presence of $[RuCl_2(p\text{-cymene})]_2$, $AgSbF_6$ and $Cu(OAc)_2.H_2O$ in DCE at 100 °C in air furnished the desired product **165** in 97% yield (Scheme 57). Interestingly, electron-rich substrates such as *N*-*tert*butoylindole and *N*-Boc-indole only furnished trace amounts of the C-2 alkenylated products.



163 **164** (1.2 equiv) **165** : 97%

Scheme 57

Aromatic esters can undergo oxidative alkenylation with various acrylates.[116] The catalytic system involves $[RuCl_2(p\text{-cymene})]_2$, $AgSbF_6$ and co-catalytic amount of $Cu(OAc)_2.H_2O$ in the presence of air. Aromatic esters containing various substituents were functionalised selectively on the *ortho* position (Scheme 58). Intermolecular competition experiments between differently substituted benzoates showed electron rich esters to be preferentially alkenylated.

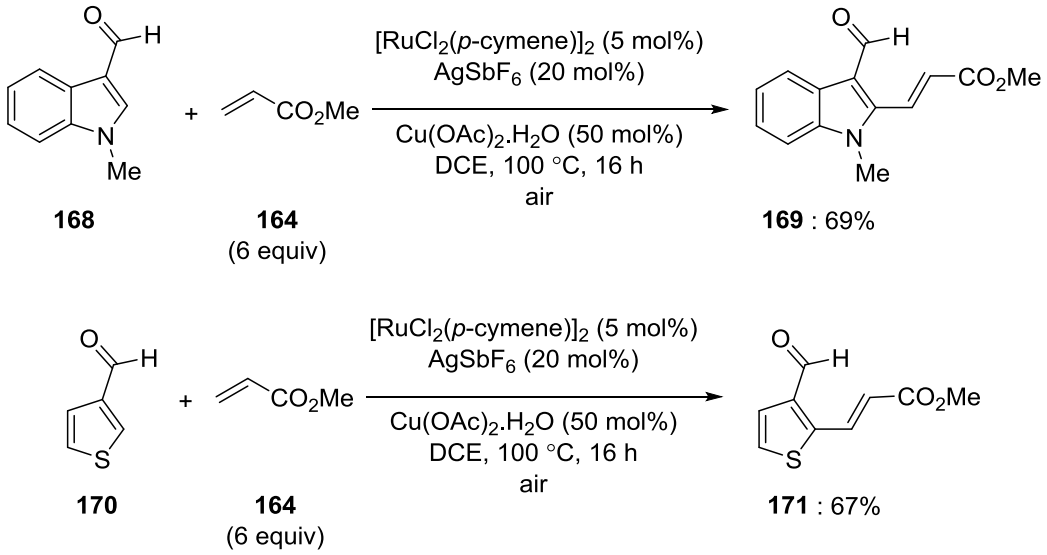


166 **155** (2 equiv) **167** : 62%

Scheme 58

Other weak coordinating directing groups such as aldehydes are also viable directing groups for C-H alkenylation with activated alkenes.[117] Various aromatic aldehydes reacted with acrylates in the presence of $[RuCl_2(p\text{-cymene})]_2$, $AgSbF_6$ and $Cu(OAc)_2.H_2O$ under an atmosphere of air to provide substituted alkene derivatives in good to high yields in a regio- and stereoselective fashion.[117] Moreover, aldehydes were compatible for alkenylation, as demonstrated by 1-methylindole-3-

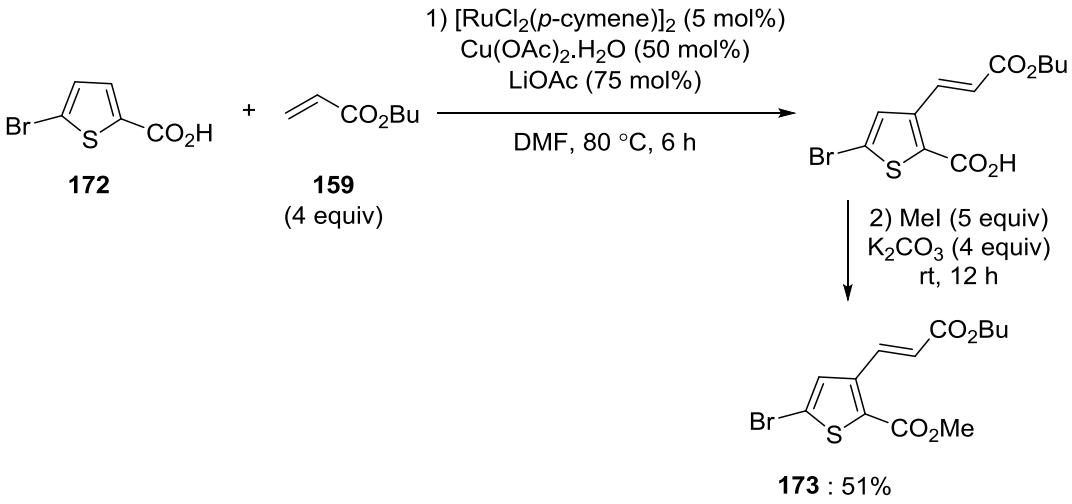
carboxaldehyde **168** and 3-formylthiophene **170**, which underwent oxidative alkenylation to give the corresponding products **169** and **171** in 69 and 67% respectively (Scheme 59).



Scheme 59

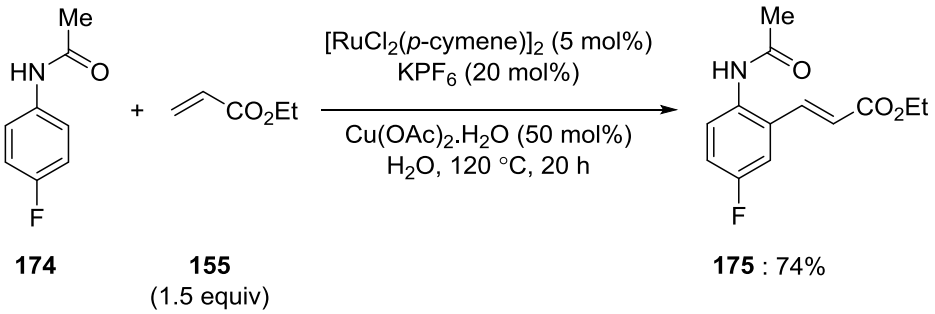
Lanke and Prabhu have also employed aldehyde as a directing group for functionalising indoles on the C-4 position.[118] This reaction is versatile as a variety of activated alkenes are compatible in the reaction including styrene, acrylonitrile and vinyl phosphonates. It is worth noting that the present method has applications for synthesising alkaloids and related heterocyclic compounds.

In 2011, Miura *et al.* described C-H alkenylation of heteroaromatic carboxylic acids.[119] Heteroarenes such as thiophenes, benzofuran-, pyrrole and indole carboxylic acids can undergo regioselective *ortho*-alkenylation followed by methyl esterification using iodomethane and K_2CO_3 to provide 3-alkenylated products (Scheme 60).



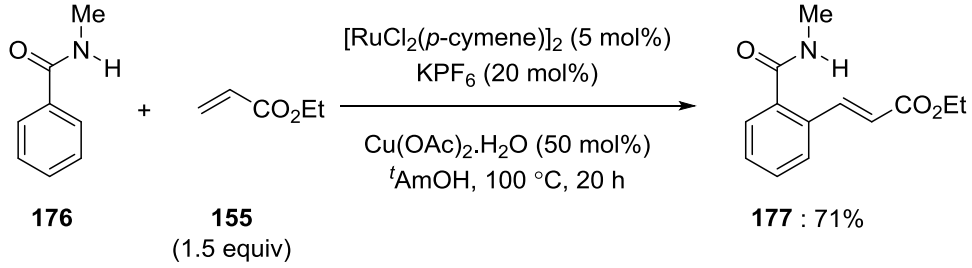
Scheme 60

In 2012 Ackermann and co-workers developed a protocol for the direct C-H alkenylation of anilides performed in water.[120] Various anilides were efficiently converted to the monoalkenylated products (Scheme 61). Intermolecular competition experiments revealed electron-rich anilides to be preferentially functionalised which indicates an electrophilic activation step. Moreover, in the presence of the cationic ruthenium complex, the anilide and D_2O as the solvent, H/D exchange was observed on the substrate indicating a reversible cyclometallation.



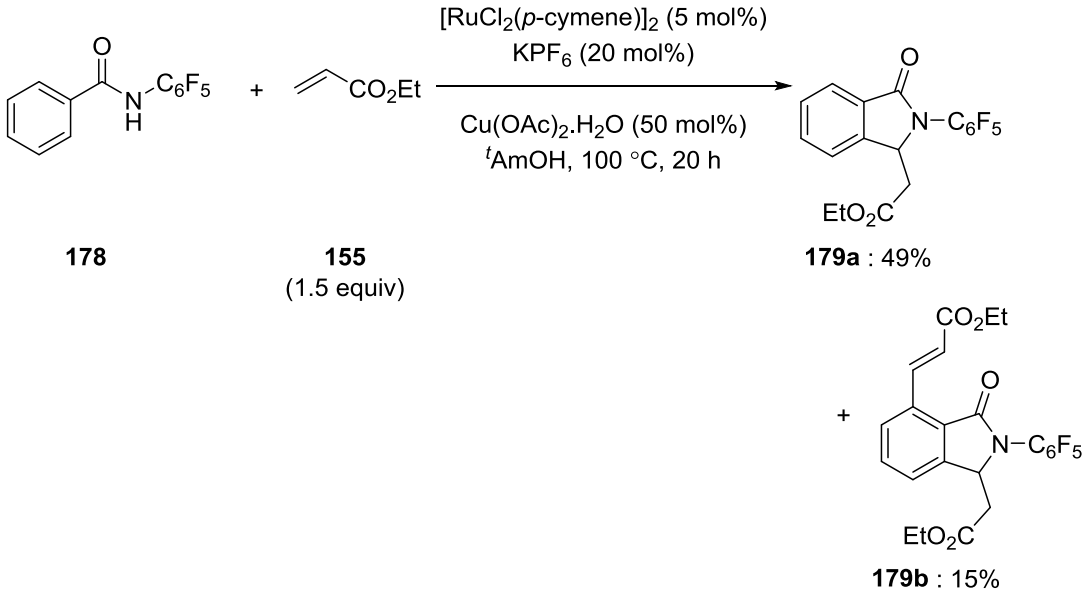
Scheme 61

The same catalytic system was compatible for oxidative alkenylation of benzamides as well (Scheme 62). *N*-pentafluorophenylbenzamide **178** was a viable substrate and delivered two different lactams **179a** and **179b** as products *via* intramolecular aza-Michael addition (Scheme 63). Mechanistic studies with isotopically labelled benzamides suggested the metallation step is irreversible with a KIE of $k_H/k_D \approx 5.4$.



176 **155** (1.5 equiv) **177** : 71%

Scheme 62

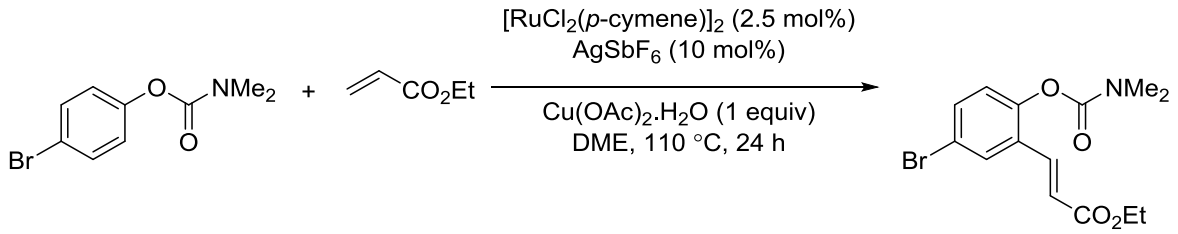


178 **155** (1.5 equiv) **179a** : 49%

179b : 15%

Scheme 63

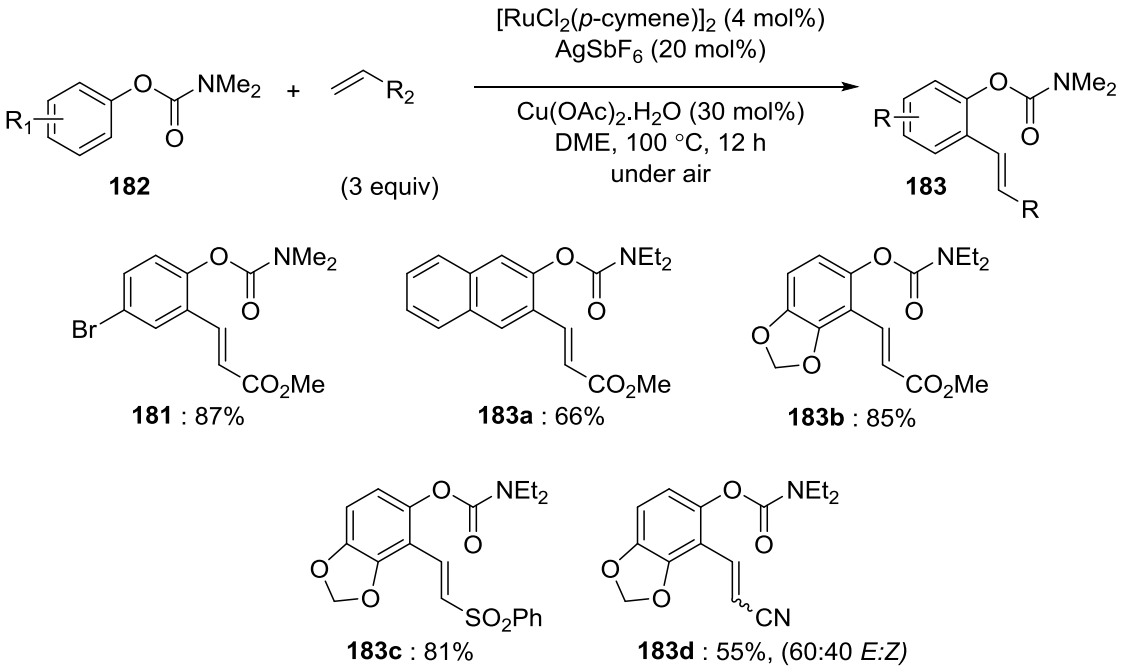
Phenol derivatives can be accessible by utilising carbamates as a masked directing group. The research groups of Ackermann[121], Jeganmohan[122] and Li[123] independently disclosed reaction conditions for the direct functionalisation of carbamates. The three research groups adopt the cationic ruthenium(II) catalyst to perform the *ortho* alkenylation. The work by Ackermann's group reacts a range of carbamates with acrylates in the presence of 2.5 mol% of $[RuCl_2(p\text{-cymene})]_2$, 10 mol% of $AgSbF_6$ and 1 equivalent of $Cu(OAc)_2.H_2O$ in DME at 110 °C for 24 hours.[121] The reaction displayed a broad substrate scope where valuable functional groups were tolerated, substituents such as fluoride, chloride and bromide remained intact in the reaction and the products were obtained with high regioselectivity and yield (Scheme 64).



180 **155** (2 equiv) **181** : 61%

Scheme 64

In contrast, Jeganmohan's study[122] was more in-depth and the reaction conditions are somewhat similar to Ackermann's work, except the oxidative coupling of aryl carbamates with acrylates was performed with a higher loading of catalyst and additives plus the reaction time is shorter, but the catalytic efficiencies are similar. Reaction between 2-napthyl diethylcarbamate and methyl acrylate reacted at the less hindered C-H bond to afford **183a** in 66% yield. Interestingly when methyl acrylate reacted with the unsymmetrical sesamol carbamate, functionalisation took place exclusively at the sterically congested C-H bond providing the product with high regioselectivity. Other substituted alkenes reacted with sesamol carbamate including 2-hydroxyethyl acrylate and activated alkenes such as phenyl vinyl sulfone and acrylonitrile were also compatible under the present catalytic system. However, acrylonitrile provided a mixture of *E*/*Z* isomers **183d** in a total yield of 55% with a ratio of 60:40 of the two isomers. Styrenes and 4-chlorostyrene were also suitable coupling partners for the reaction (Scheme 65).



182 (3 equiv) **183**

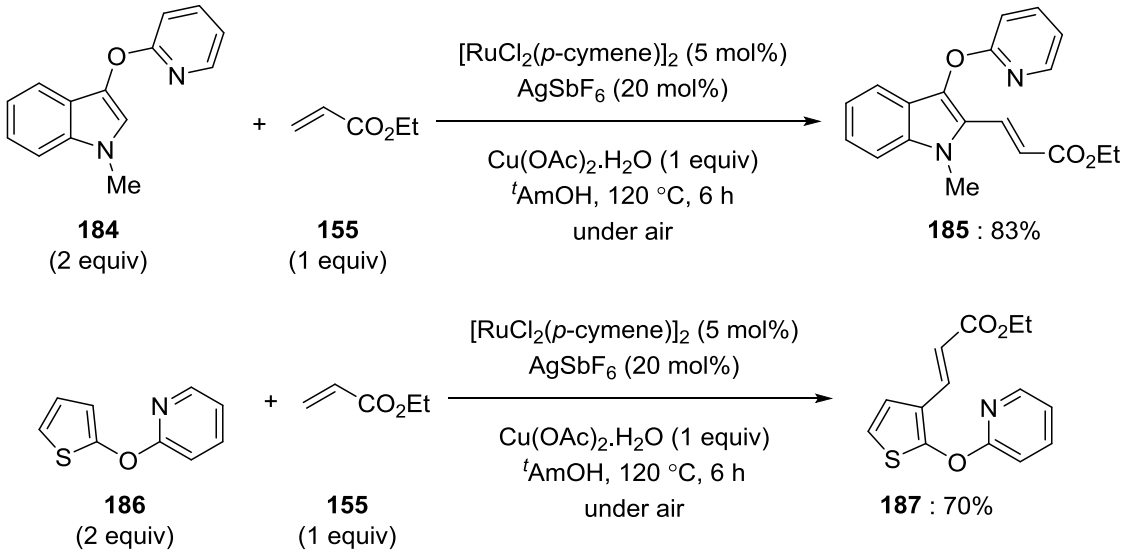
181 : 87% **183a** : 66% **183b** : 85%

183c : 81% **183d** : 55%, (60:40 *E:Z)*

Scheme 65

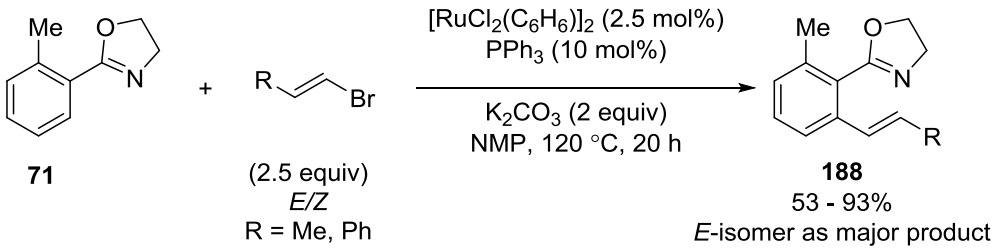
The catalytic system developed by Li, differs with the use of THF as the solvent. Although Li's catalytic system provides slightly higher yields compared to Ackermann's and Jeganmohan's works, but this can be attributed with the long reaction time of 30 hours, making Li's system more time consuming to reach good productivity.[123]

Pyridine can also be used as a removable directing group for the functionalisation of phenols as demonstrated by Ma and Ackermann.[124] 2-Aryloxypyridine can undergo oxidative alkenylation with a cationic ruthenium complex. The reaction is highly chemo- and regioselective and only the monoalkenylated products are obtained. Heteroarenes are also suitable substrates; indole **184** and thiophene **186** delivered the *ortho*-olefinated products **185** and **187** in 83% and 70% yields respectively. The 2-pyridyloxy-directing group can be easily cleaved to deliver the free phenol (Scheme 66).



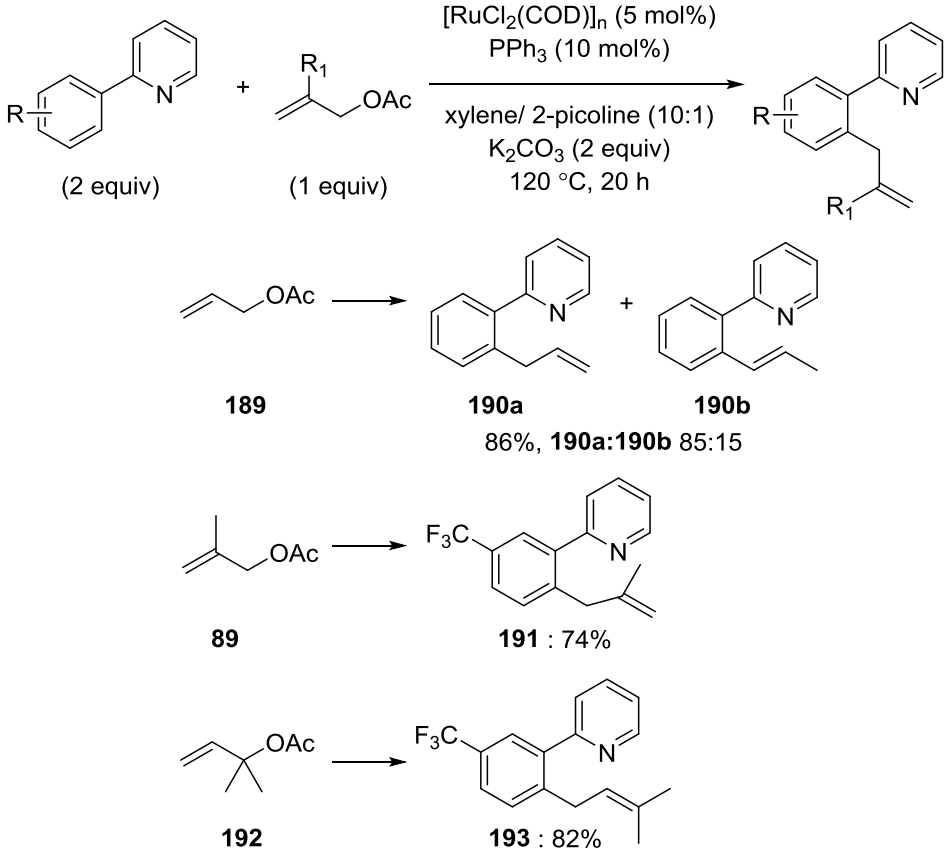
Scheme 66

In 2005 Oi and Inoue developed a catalytic reaction of aryloxazoline and alkenyl bromides to afford *ortho*-alkenylated products often as a mixture of *E*/*Z* products due to isomerisation of the alkene (Scheme 67).[76] This catalytic system was compatible to 2-arylimidazolines, affording good to excellent yields of arylated products. It was proposed that the key intermediate is a Ru(IV) species and the cyclometallation takes place first, followed by reductive elimination to give the alkenylated product.



Scheme 67

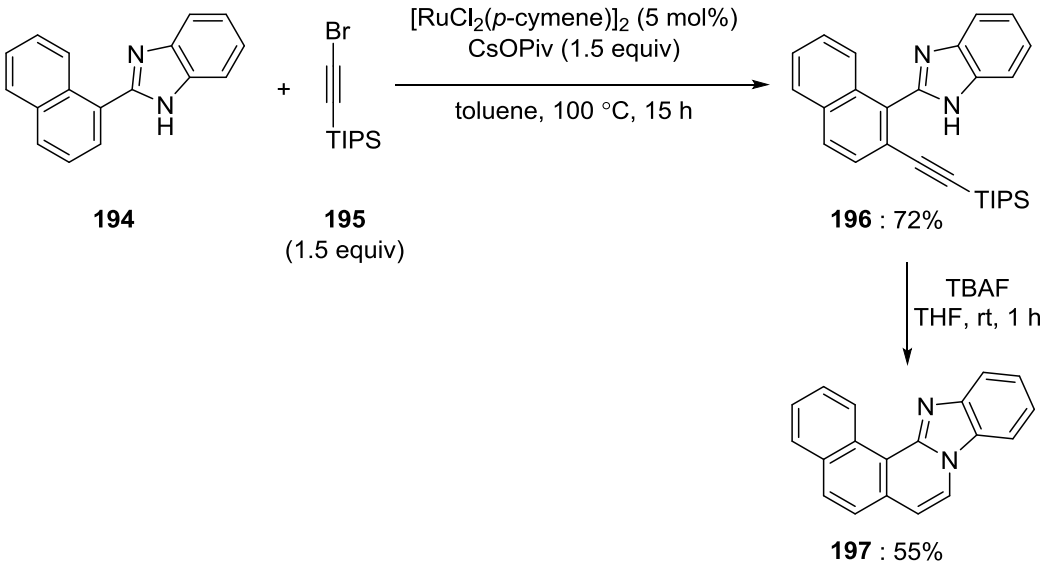
Oi and Inoue *et al.* have also investigated a Ru(II) catalysed *ortho* allylation also using a PPh_3 as the ligand at 120 ^{o}C. 2-Phenylpyridine was used as the substrate and when a linear allyl acetate was used, two products were produced, the *ortho*-allylated product together with the isomer, for example, 2-phenylpyridine with allyl acetate **189** and produced the desired product **190a** and its isomer **190b** in a total yield of 86% in a ratio of 85:15.[125] In contrast, the branched allyl acetate afforded the linear allylated products exclusively. The mechanism is expected to proceed *via* cyclometallation followed by allyl acetate oxidative addition and subsequent reductive elimination (Scheme 68).



Scheme 68

1.2.5. Ru(II) catalysed sp^2 C-H alkynlation

At present there is only one example ruthenium catalysed C-H alkynylation reported.[126] Reaction of 2-(2-methylphenyl)pyridine with silyl-protected alkyne in the presence of $[RuCl_2(p\text{-cymene})]_2$ and CsOPiv as the base in toluene at 100 °C for 15 hours, gave the alkynylated product in 74% yield. Under the same catalytic system other substrates can also perform the alkynylation reaction, including arylpyrimidine, arylpyrazole, arylimidazole, aryloxazoline and benzo[*h*]quinoline. However all of the substrates with the exception of benzo[*h*]quinoline, requires a methyl substituent on the 2-position of the aryl ring to suppress the formation of the dialkynylated product. Another disadvantage to this reaction is this method requires a bulky tri*iso*propylsilyl protected alkyne **195** as the coupling partner, which makes this reaction limited, as other alkynes cannot be employed. Despite that, this reaction does have synthetic applications, as the protecting group can be easily cleaved with TBAF to reveal the terminal alkyne and can be used for further synthesis (Scheme 69).



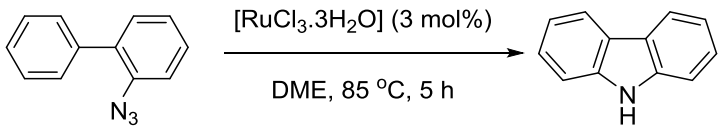
194 **195** (1.5 equiv) **196** : 72% **197** : 55%

Scheme 69

1.2.6. Ru(II) catalysed sp^2 C-H amination, amidation and cyanation

At present there are few examples of Ru-catalysed C-H amination.[127] One example of C-H amination was reported in 2009, by Lin and Jia *et al.*, it was found that $RuCl_3$, a ruthenium(III)

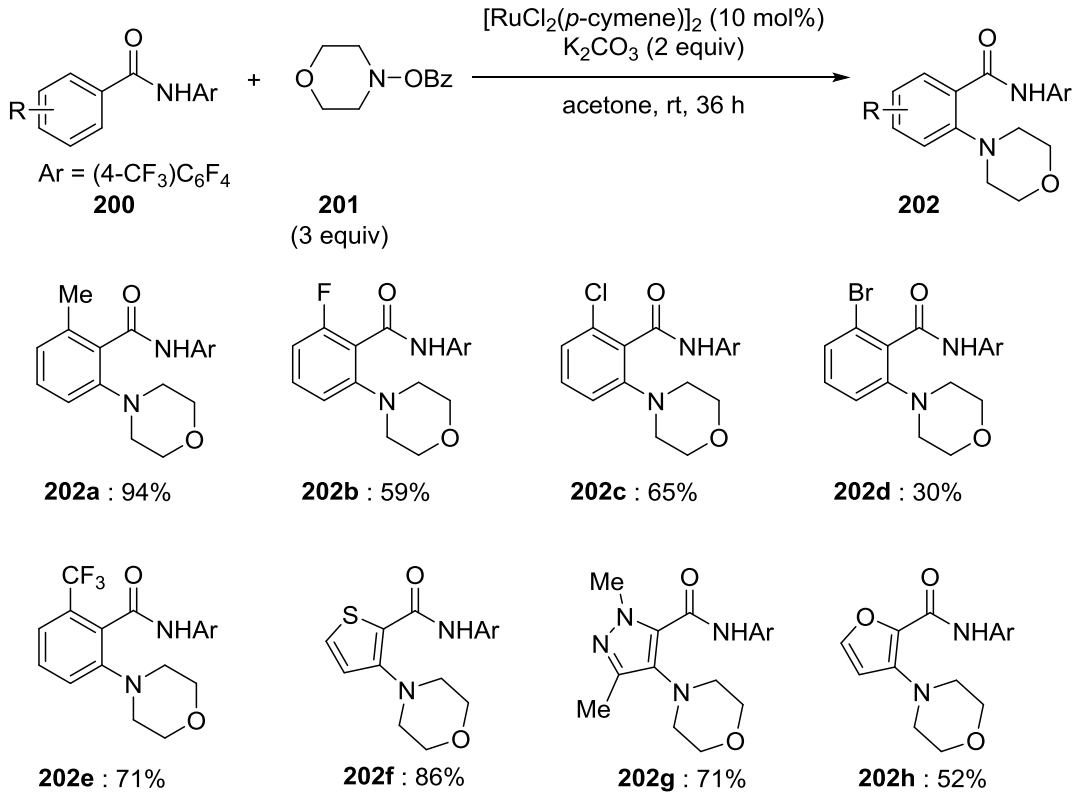
catalyst to promote *ortho*-C-H amination on *ortho*-aryl phenyl azides, 1-azido-2-arylvinylazides and 1-azido-1,3-butadienes to give the corresponding, carbazoles, indoles and pyrroles respectively (Scheme 70).[128]



198 **199** : 90%

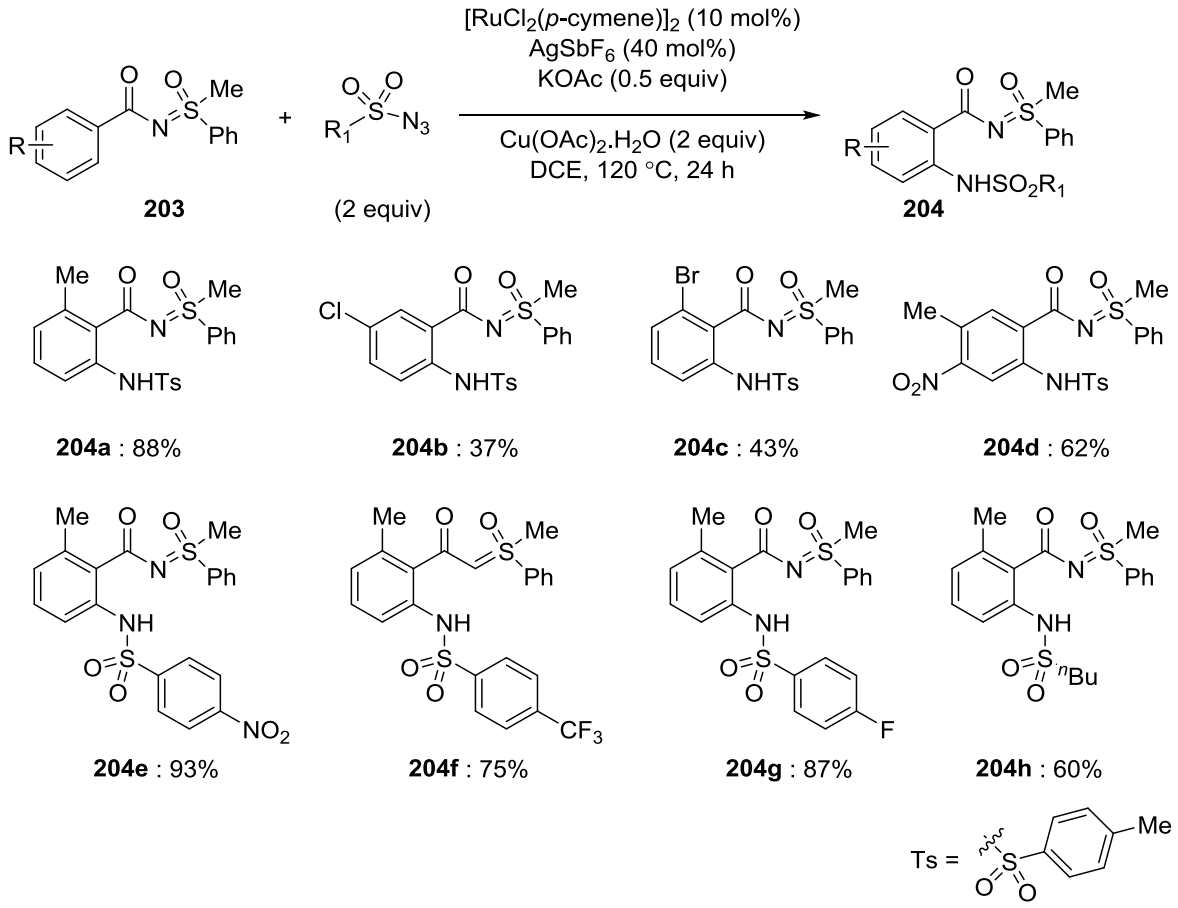
Scheme 70

In 2013, Yu *et al.* reported a Ru(II) catalysed C-H amination of aryl amides.[129] This methodology is more efficient as it is carried out at room temperature and in acetone, making it a very mild reaction compared to other C-H functionalisation reactions. However, due to the low temperature a longer reaction time of 36 hours is required. Both fluorinated and chlorinated arenes reacted and provided the corresponding aminated products in 40 – 69% yields. Whereas, brominated arenes were less compatible, and gave low yields. Other heterocyclic substrates were complementary to the C-H amination under the same reaction conditions; heteroarenes including pyrazole, thiophene, benzothiophene, furan and indole were all compatible in this reaction (Scheme 71).



Scheme 71

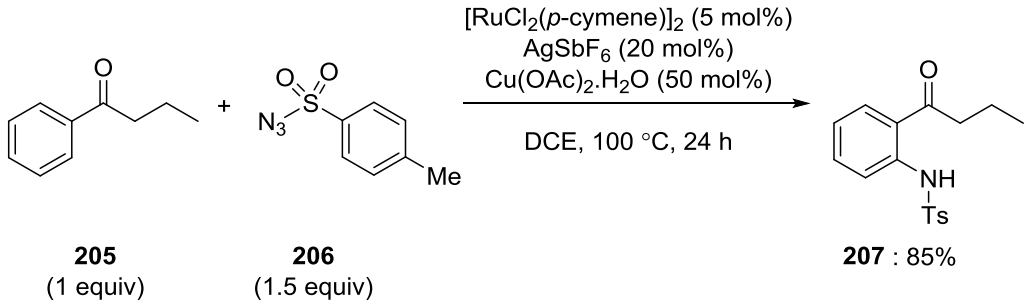
More recently, there have been several reports of *ortho*-C-H amidation of arenes with sulfonyl azides. Sahoo and co-workers reported *ortho*-amidation of arenes, using sulfoximine as a directing group for the reaction.[130] This reaction works by employing an *in situ* generated cationic Ru(II) complex, in the presence of 10 mol% of $[RuCl_2(p\text{-cymene})]_2$ and 40 mol% of $AgSbF_6$, as well as a base KOAc (0.5 equivalents) in DCE at 120 °C for 24 hours to give the regioselective *ortho*-C-N bond formation of the arene. The reaction proceeds with broad substrate scope and tolerates various functional groups. It was shown that electron-deficient substituents such as NO_2, F and CF_3 did not affect the reaction efficiency. In addition, a range of sulfonyl azides were compatible in the reaction, the more electrophilic sulfonyl azides performed well as coupling partners, moreover, aliphatic sulfonyl chlorides produced the amidation product albeit in slightly lower yield (Scheme 72).



Scheme 72

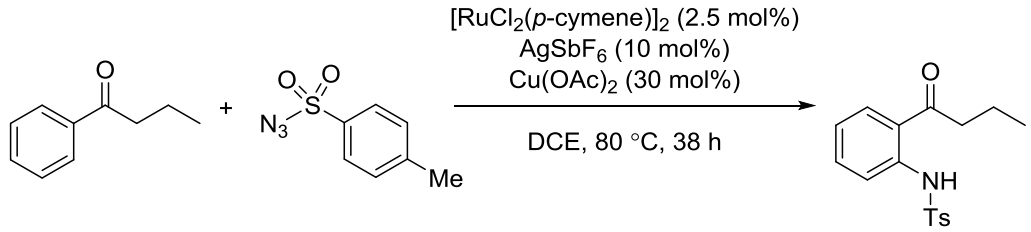
Sahoo,[131] Ackermann,[132] Chang and Jiao,[133,134] all have independently reported C-H amidation of arenes using sulfonyl azides under similar reaction conditions, using an *in situ* generated cationic Ru(II) complex. Sahoo and co-workers reported the *ortho*-C-H amidation of aromatic ketones only.[131] On the other hand, Jiao and co-workers have also reported *ortho* amidation of aromatic ketones, but compared to the study by Sahoo, Jiao's catalytic system is more efficient and cost effective as the catalyst loading and additives used are much less in comparison to Sahoo's system (Scheme 73). [134]

Sahoo's work



205 (1 equiv) **206** (1.5 equiv) **207** : 85%

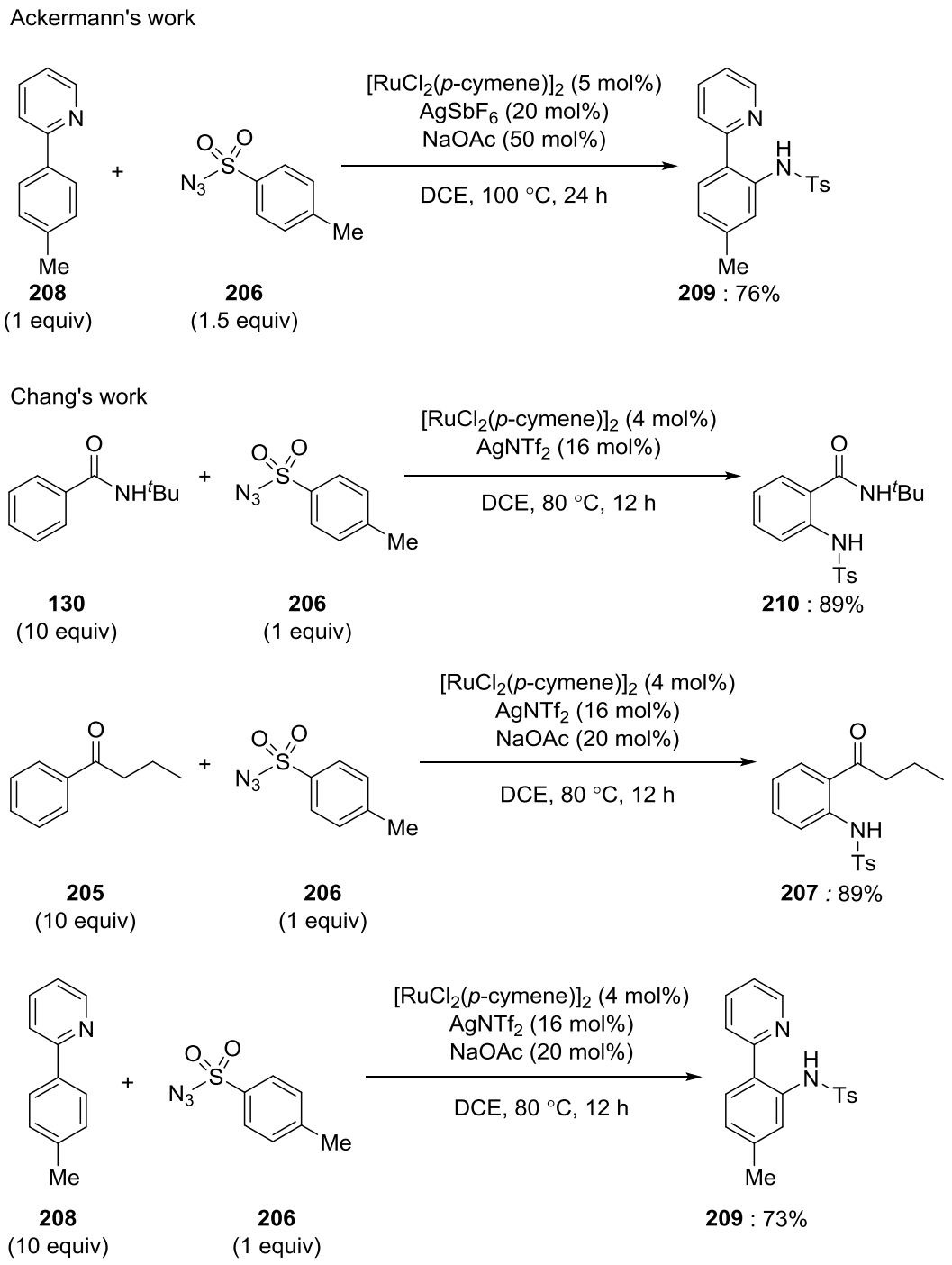
Jiao's work



205 (1 equiv) **206** (2 equiv) **207** : 81%

Scheme 73

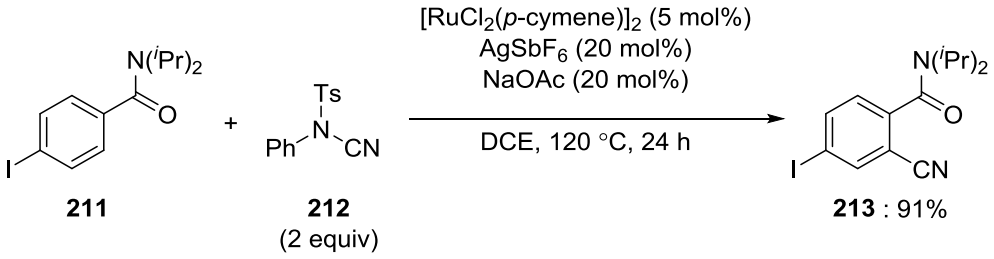
In contrast Ackermann and co-workers performed C-H amidation on heteroaryl-substituted arenes, including, pyrazoles, pyrimidines and pyridines.[132] Conversely to the study by Chang,[133] it has demonstrated *ortho*-C-H amidation on a range of directing groups, including weakly coordinating aryl ketones, benzamides, aryl pyridines, aryl pyrazoles and aryl imines. The reaction is carried out at 80 °C making this reaction mild in comparison to Sahoo and Ackermann's conditions.[131, 132] However, one main disadvantage to Chang's reaction is that the limiting reagent is the sulfonyl azide, and the substrate is used in excess (10 equivalents); whereas for the other two studies, the substrate is the limiting reagent, and not the sulfonyl azide (Scheme 74).



Scheme 74

Very recently, the first example of ruthenium(II) catalysed C-H cyanation was reported by Ackermann and co-workers.[135] Direct cyanation was performed on the weakly coordinating aromatic amides such as **211**, with $[RuCl_2(p\text{-cymene})]_2$, $AgSbF_6$ and NaOAc and *N*-cyano-*N*-phenyl-*para*-toluenesulfonamide as the cyanation reagent in DCE at 120 °C for 24 hours. This catalyst system tolerated a range of electrophilic functional groups, such as ester, fluoro, chloro, bromo as well as iodo groups, which could be used for further functionalisation of the obtained products.

The reaction also reacts efficiently with heteroaromatic amides. Thereby, thiophenes, furanes, benzothiophenes, benzofuranes and indoles, have all furnished the corresponding cyananted products in a chemo- and site-selective manner (Scheme 75).



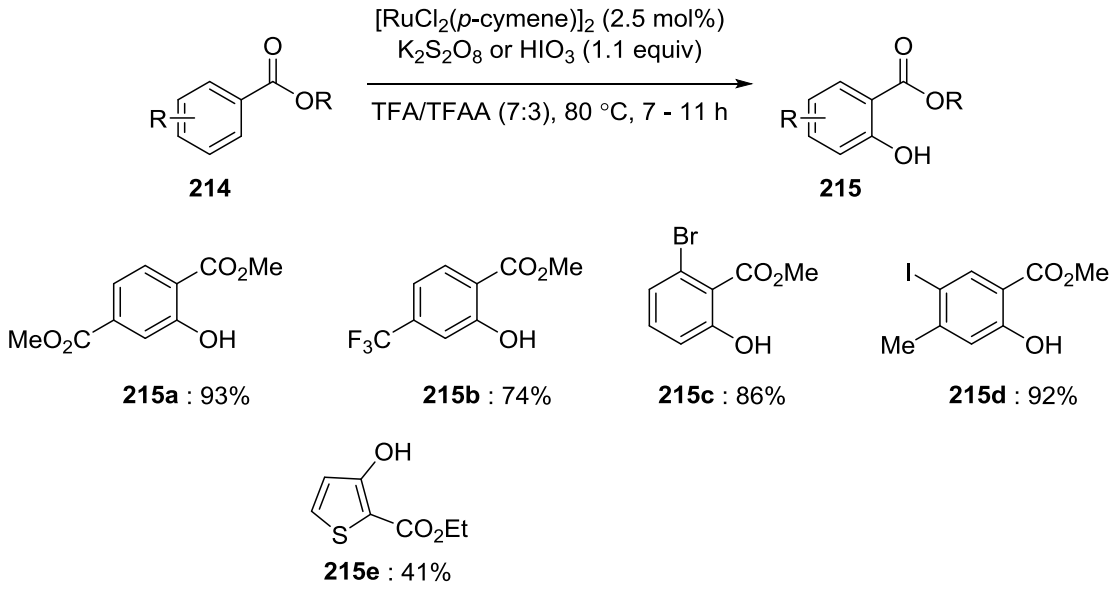
Scheme 75

1.2.7. Ru(II) catalysed *sp²* C-H hydroxylation and benzoxylation

The past few years have witnessed progress in the direct hydroxylations of *sp²* C-H bonds in arenes and heteroarenes with ruthenium catalysts.[127] Both the Rao group and Ackermann group have made a lot of contributions in this field of research.

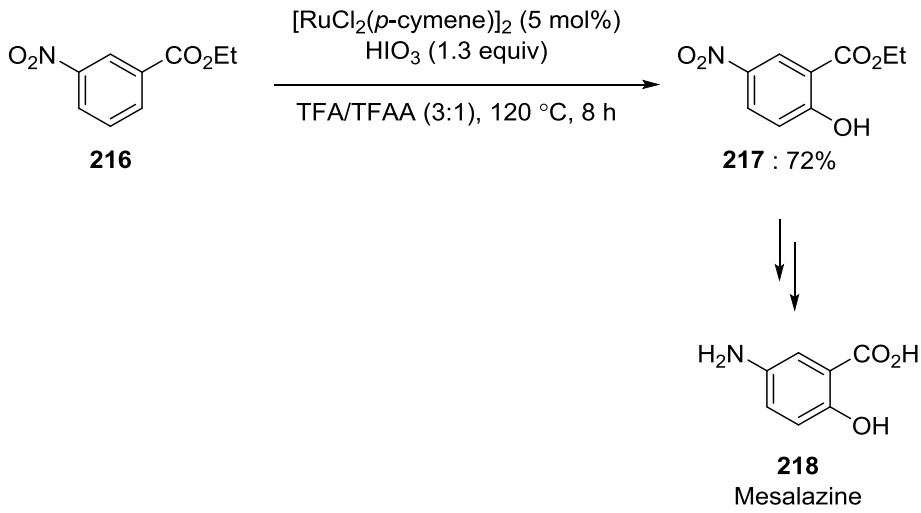
Rao and co-workers utilised $[RuCl_2(p\text{-cymene})]_2$ as the precatalyst and $K_2S_2O_8$ or HIO_3 as the oxidant. In contrast Ackermann and co-workers have employed various ruthenium catalysts depending on the substrate, the catalysts employed include $[RuCl_2(p\text{-cymene})]_2$ as well as the well-defined ruthenium complexes $[Ru(O_2CMes)_2(p\text{-cymene})]$ or $RuCl_3.(H_2O)_n$ and a source of hypervalent iodine as the oxidant. Interestingly for the C-O bond formations on arenes, the solvent mixture comprising of TFA/TFAA is critical for the success of this transformation.

The Rao group studied the hydroxylation of esters, ketones and anilides. The ruthenium-catalysed *ortho*-hydroxylation of benzoates **214** was found to be generally useful for the preparation of multi-functionalised arenes, some of which are difficult to synthesise *via* conventional methods.[136] The reaction demonstrated a good functional group tolerance and provided the products in high yields (Scheme 76).



Scheme 76

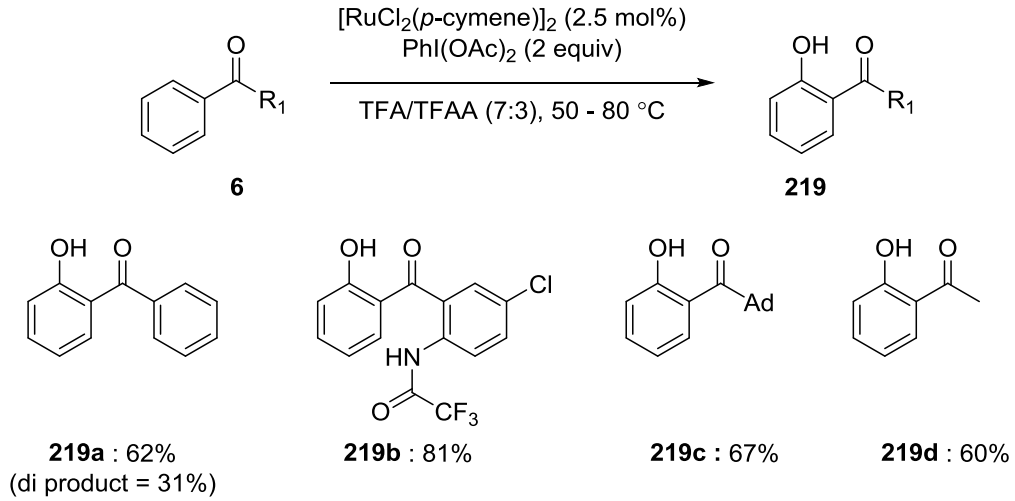
The reaction has synthetic applications for the construction of biologically important molecules, ethyl 3-nitrobenzoate **216** underwent hydroxylation followed by sequential hydrolysis and reduction to give Mesalazine **218**, an anti-inflammatory drug (Scheme 77).



Scheme 77

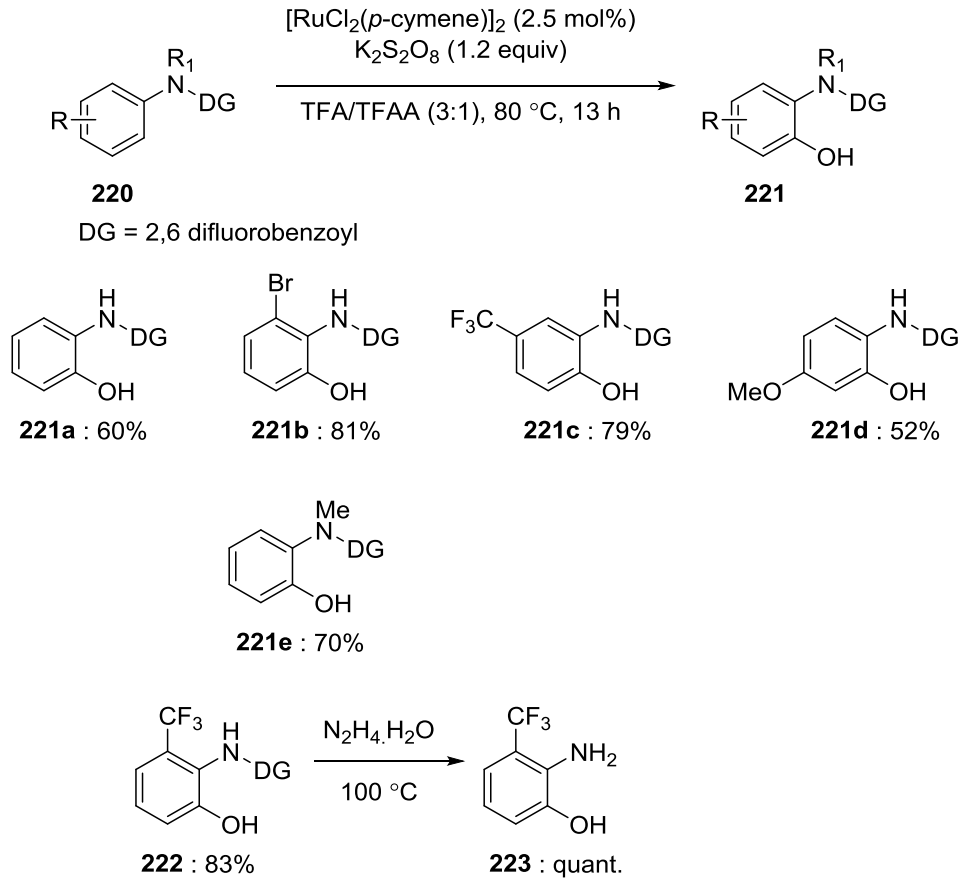
This chemistry can be extended to the weakly coordinating carbonyl group as demonstrated with the oxygenation of aryl ketones **6** under milder conditions, in which the reaction is performed at lower temperatures of 50 – 80 °C and provides the 2-acyl phenols **219** in high site-selectivity and moderate to good yields (Scheme 78).[137] Besides the expected monohydroxylated product, a

considerable amount of the dihydroxylated product was also formed. The reaction exhibited good functional group tolerance and the reaction was applied in gram-scale syntheses of 2-acyl phenols using a lower catalyst loading of 1 mol% of $[RuCl_2(p\text{-cymene})]_2$.



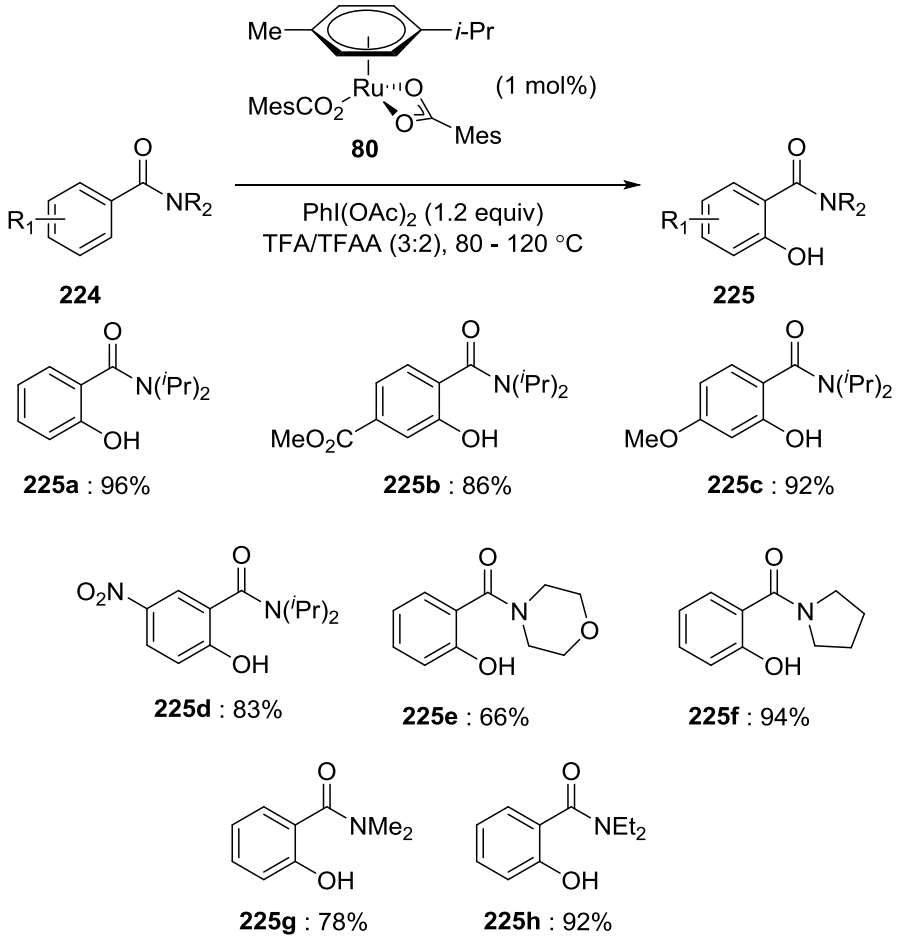
Scheme 78

Synthesis of 2-aminophenols and heterocycles can be achieved through Ru-catalysed C-H mono- and dihydroxylation of anilides by employing 2,6-difluorobenzoyl groups as the removable directing group.[138] The regioselectivity of the reaction can be tuned accordingly with the amount of the oxidant used. When 1.2 equivalent of $K_2S_2O_8$ is used in the reaction, the monohydroxylated product is obtained, on the other hand, by increasing the amount of oxidant to 3 – 4 equivalents, the dihydroxylated compound is the sole product. The reaction is practical as the hydroxylated products can be used to synthesise heterocycles, such as dibenzoxazopine and benzoxazole. Moreover, the amide directing group can be easily cleaved by hydrazinolysis to reveal the free amino group (Scheme 79).



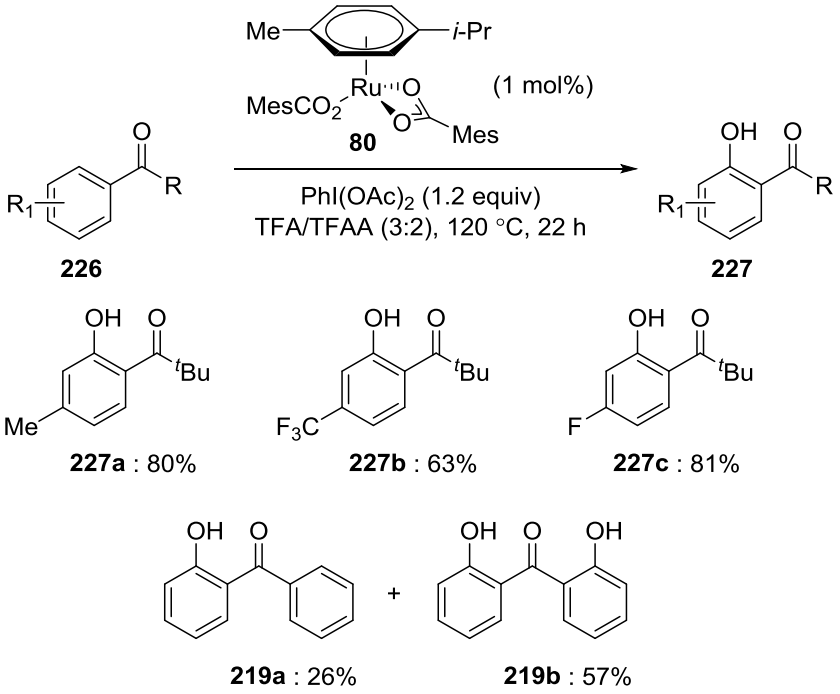
Scheme 79

In 2012, Ackermann and co-workers described the Ru-catalysed C-H oxygenation of benzamides **224** to give the site-selective C-O bond formation.[139] The oxidative C-O bond formation was accomplished with $PhI(OAc)_2$ as the oxidant and $RuCl_3(H_2O)_n$ as the catalyst. However, the well-defined biscarboxylate ruthenium complex **80** provided the best catalytic system with good results for the *ortho*-hydroxylation of benzamides. Various *N,N*-disubstituted benzamides including dimethylamino, di*iso*propylamino, pyrrolidinyl or morpholinyl moieties afforded the corresponding hydroxylated products in good to excellent yields (Scheme 80).

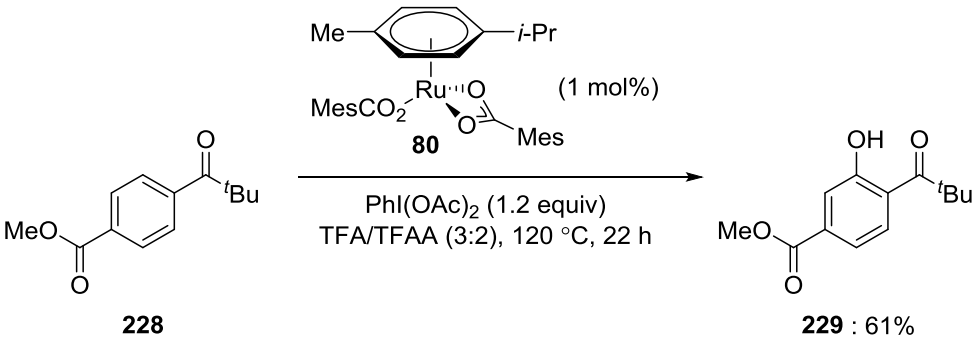


Scheme 80

The biscarboxylate ruthenium complex **80** was exploited in the search for other substrates for hydroxylation and found the weakly coordinating ketones in phenones were also applicable in the ruthenium-catalysed hydroxylation.[140] The hydroxylation worked with excellent functional group tolerance and broad substrate scope as well as chemo- and site-selectivities (Scheme 81). Compared to the study by Rao, the present hydroxylation of benzophenone furnished both the mono- and dihydroxylated products, Rao[137] only observed the monohydroxyated product. A competitive experiment on a substrate containing two directing groups, clearly showed the superior directing group ability of the *tert*-butyl ketone compared to an ester moiety (Scheme 82).

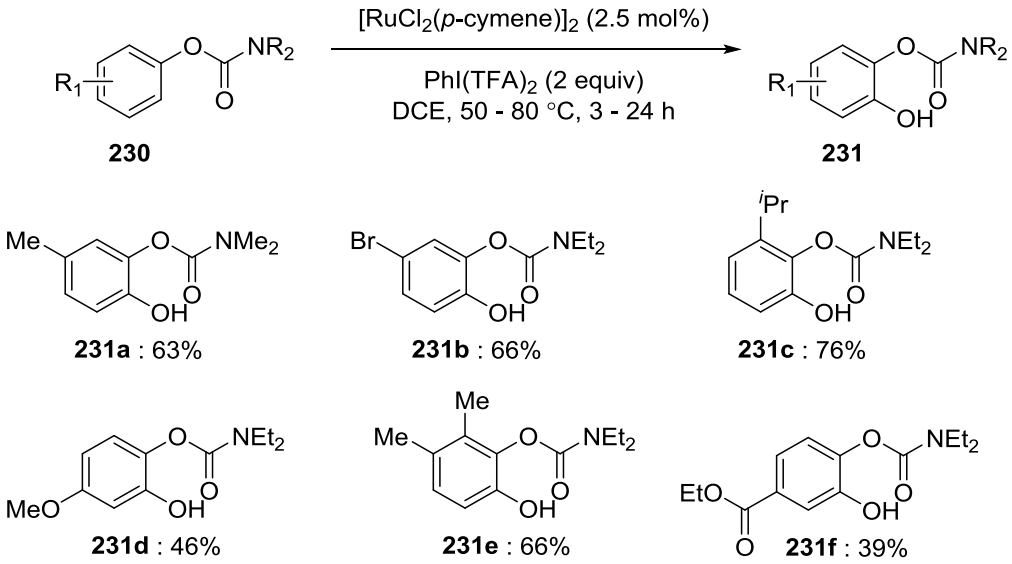


Scheme 81



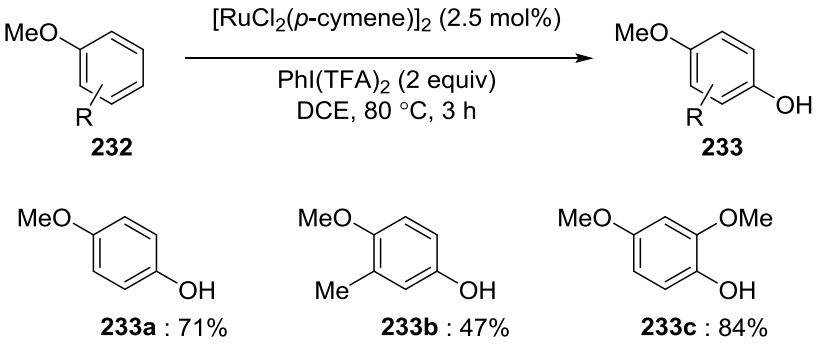
Scheme 82

Recently Ackermann and co-workers reported the first ruthenium-catalysed hydroxylation of phenol derivatives under remarkably mild reaction conditions.[141] The direct hydroxylation of aryl carbamates **230** delivered the *ortho*-monohydroxylated product **231** with high catalytic efficiency as well as high chemo- and regioselectivities (Scheme 83). The reaction tolerated various functional groups including chloro, bromo and iodo substituents. Studies with isotopically labelled substrate disclosed a KIE of $k_H/k_D \approx 2.2$, which suggests a kinetically relevant C-H metallation step.



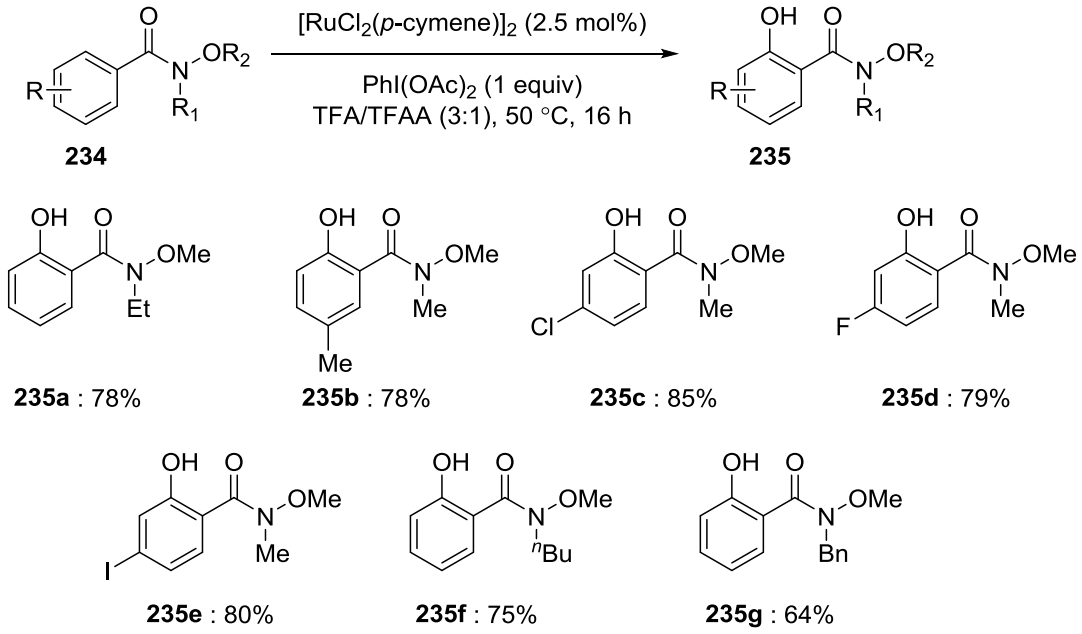
Scheme 83

The catalytic system was amenable to anisole derivatives **232**, which occurred with *para*-selectivity (Scheme 84).



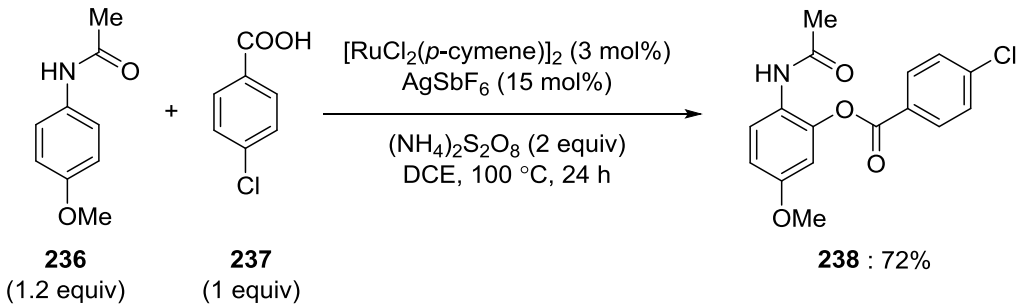
Scheme 84

Ackermann and co-workers have also reported the first example of C-H oxygenation of aryl Weinreb amides **234** under mild conditions thereby giving access to *ortho*-hydroxylated aldehydes post C-H functionalisation.[142] In the presence of $[RuCl_2(p\text{-cymene})]_2$ along with $PhI(OAc)_2$ as the oxidant in TFA/TFAA at 50 °C, the methodology provided the desired products with wide substrate scope. Halogen substituents such as F, Cl and I were tolerated well in the reaction and obtained the corresponding hydrogenated products in good yields (Scheme 85).



Scheme 85

Recently, Jeganmohan *et al.* described the ruthenium-catalysed benzoxylation of acetamides with benzoic acids to provide *ortho*-benzoxylated acetanilides in moderate to good yields.[143] The catalytic reaction was revealed to be highly sensitive to the substituents present on the aromatic acid. Strong electron-donating and electron-withdrawing substituents such as OMe, NO_2, CN and COMe on the aromatic acids were not compatible in the reaction (Scheme 86).

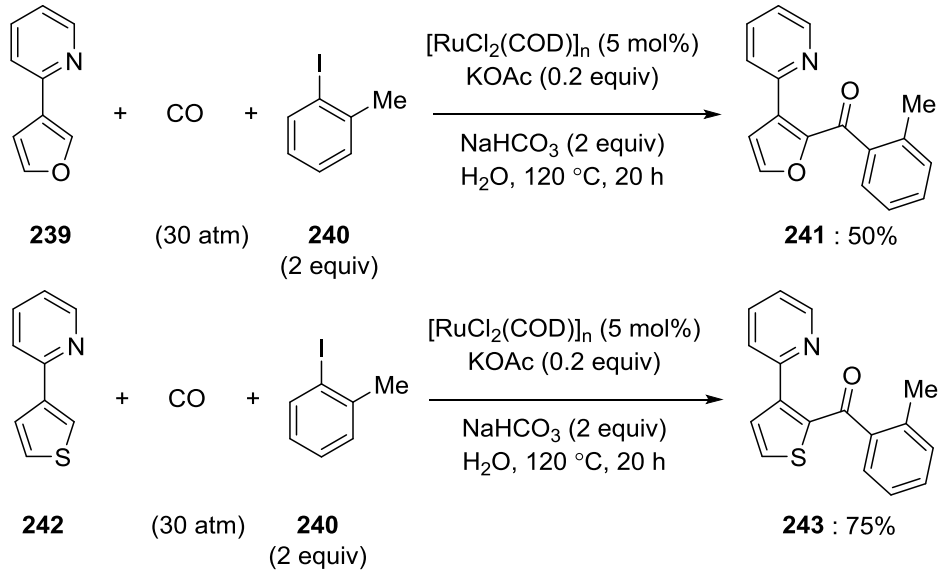


Scheme 86

1.2.8. Ru(II) catalysed sp^2 C-H carbonylation

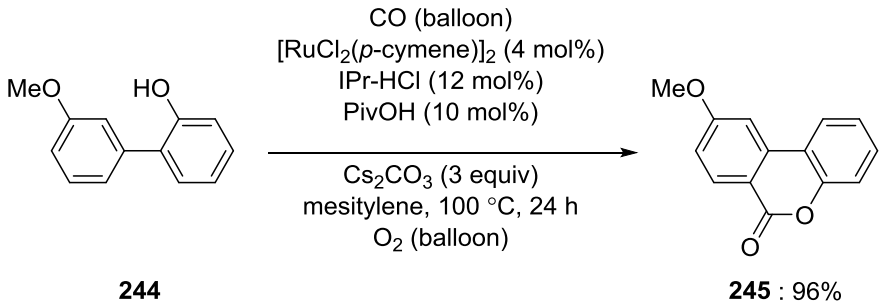
As mentioned previously, there are many examples of ruthenium(0) catalysed C-H carbonylation in the literature but are limited to aliphatic acylated products. Recently, Beller *et al.* reported the

ruthenium(II) catalysed carbonylative coupling of aryl halides with 2-phenylpyridine.[144] Unlike the method developed by Murai, the present reaction is performed in water as the reaction medium. The *ortho*-carbonylation products were obtained in moderate yields (Scheme 87). Other directing groups such as pyrazole and pyrimidine can also undergo carbonylation using this method. Interestingly, heterocycles bearing a pyridine directing group provided the carbonylated products in good yields.



Scheme 87

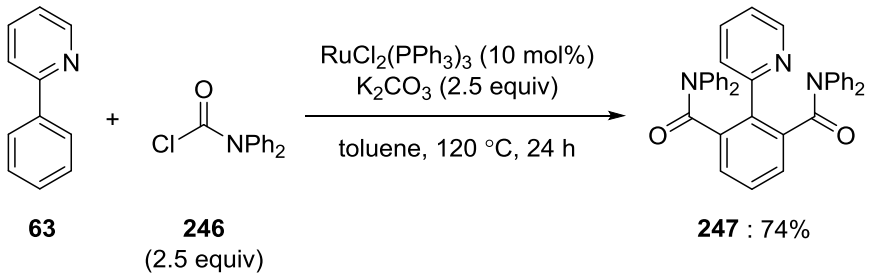
Catalytic carbonylative C-H cyclisation can be achieved in the presence of a ruthenium catalyst.[145] The reaction employs a catalytic combination of Ru/*N*-heterocyclic carbene (NHC) with a balloon pressure of CO and O_2 to promote the carbonylative C-H cyclisiation of 2-phenyl phenol **244** to afford various substituted 6H-dibenzo[*b*,*d*]pyran-6-one compounds in high yields (Scheme 88).



Scheme 88

1.2.9. Ru(II) catalysed sp^2 C-H amino-,acyloxy- and alkoxycarbonylation

Kakiuchi *et al.* described a method of preparing esters and amides regioselectively *via* C-H bond cleavage followed by coupling of chlorocarbonyl compound using a ruthenium catalyst.[146] This method differs from previous methods reported in the literature, as no oxidant is required to perform the reaction. Aminocarbonylation of benzo[*h*]quinoline was obtained in high yields. This was also true for other aromatic compounds. The reaction of 2-phenylpyridine **63** with *N,N*-diphenyl carbamoyl chloride **246** obtained both the *ortho*- monoamide and diamide products. When the starting material carbamoyl chloride was used in excess, only the diamide **247** is obtained in 74% yield (Scheme 89).

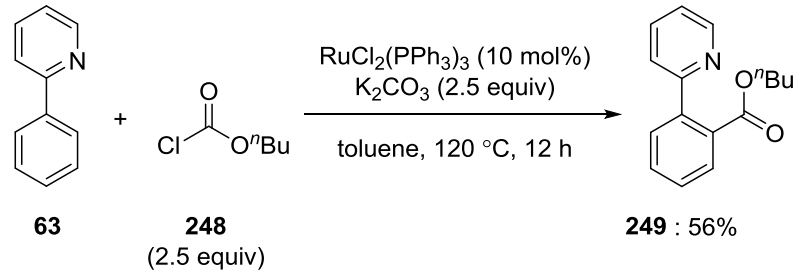


63 **246** (2.5 equiv) **247** : 74%

Scheme 89

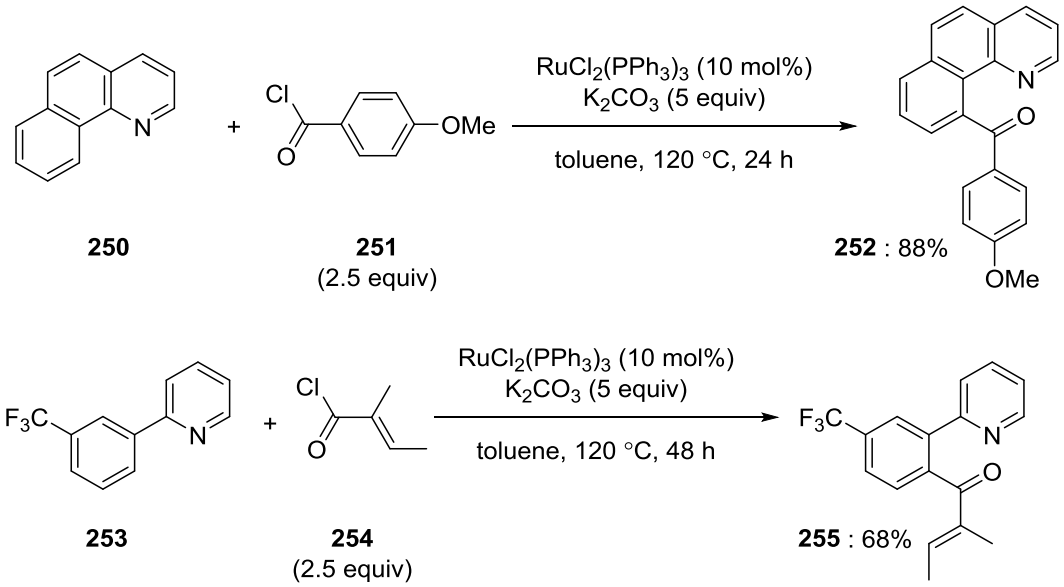
The presence of functional groups on the aryl pyridine did not hinder the reaction, for electron-donating groups such as OMe the diamide was obtained in 83% yield in 24 hours. In contrast, the CF_3 substituent also produced in a good yield of 76% of the diamide product, however the reaction time had to be prolonged to 48 hours. While the *para*-methoxyphenylpyridine gave the diamide product; both the *ortho*- and *meta*-substituted aryl pyridine produced the monoamides.

The authors also studied the alkoxycarbonylation of aryl pyridine (Scheme 90). From their findings the production of the alkoxycarbonylated product is lower than the aminocarbonylation reactions. In addition, the majority of the substituted aryl pyridines gave the *ortho* monoester product; with the exception of the *para*-trifluoromethanephenyl pyridine that formed the monoester in 47% yield plus a small amount of the diester (8% yield). Interestingly the *meta*-methyl and *meta*-trifluoromethanephenyl pyridine both produced the monoester in similar yields, despite their differing electronic properties.



Scheme 90

Recently, a CO free acylation was reported by Kakiuchi *et al.,* by employing acyl chlorides as the coupling partners.[147] Substrates such as 2-phenylpyridine and benzo[*h*]quinoline were acylated in the presence of $RuCl_2(PPh_3)_3$ and K_2CO_3 in toluene at 120 °C to afford the acylated products in moderate to good yields (Scheme 91).

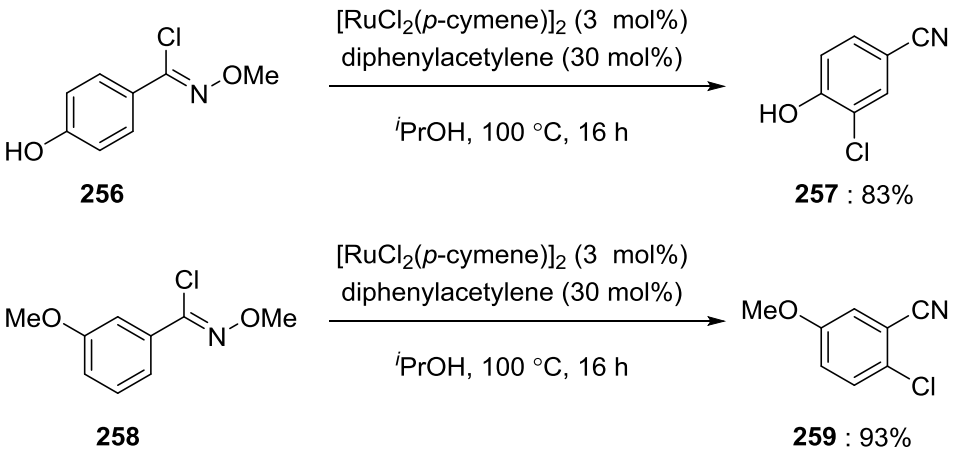


Scheme 91

1.2.10. Ru (II) catalysed sp^2 C-H halogenations

An interesting example of C-H functionalisation was reported by Jeganmohan *et al.* in 2013, in which ruthenium-catalysed halogenations were performed at the *meta* position of substituted *O*-methylbenzohydroximoyl halides in an intramolecular fashion to afford halogenated aromatic nitriles.[148] 4-Hydroxy-*N*-methoxy benzimidoyl chloride **256** undergoes halogenation in the presence of $[RuCl_2(p\text{-cymene})]_2$ (3.3 mol%) and ligand diphenylacetylene (30 mol%) in ^{i}PrOH at

100 °C for 16 hours gave the *meta*-halogenated product **257** in 83% yield in high regioselectivity. During the reaction, the imidoyl moiety is converted to the nitrile moiety to give the halogenated aromatic nitrile as the product. In contrast to the *meta*-substituted *N*-methoxybenzimidoyl chloride, the chlorination takes place at the less hindered *ortho* position. The regioselectivity of the products obtained in these present halogenations is most likely due to the *ortho* and *para* directing effects of the electron-donating groups on the aromatic ring. This methodology can also be extended to prepare *meta*- and *ortho*-bromo substituted benzonitriles in high yields and highly regioselective manner. It is noteworthy, that this reaction does not work in the presence of an electron-withdrawing group on the aromatic ring, which suggests an electrophlic aromatic substitution mechanism (Scheme 92).

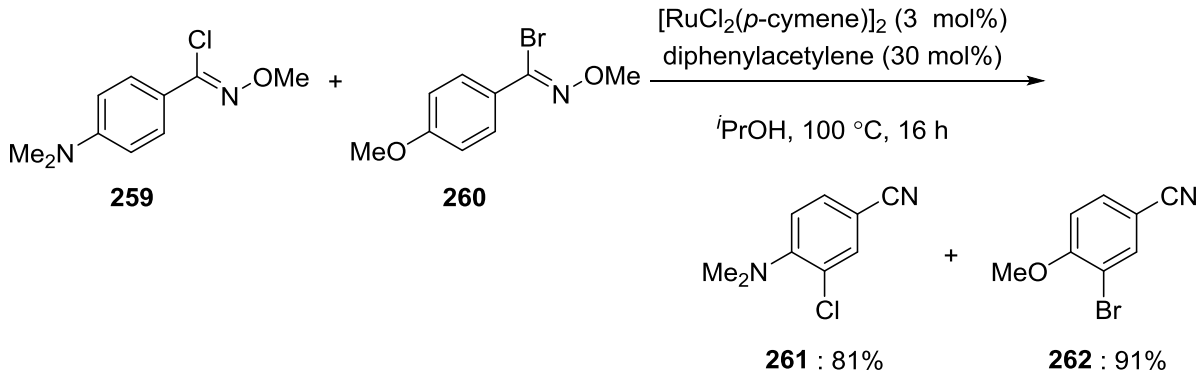


256 **257** : 83%

258 **259** : 93%

Scheme 92

Competitive experiments revealed that only the expected halogenated products were obtained and no-cross products were observed, that suggests the reaction proceeds *via* an intramolecular pathway (Scheme 93). The authors suggested that the first step in the catalytic cycle is the conversion of the imidoyl moiety to a cyano group followed by halogen transfer *via* electrophilic aromatic substitution at the *ortho* or *meta* position in the presence of the ruthenium catalyst.



Scheme 93

1.2.11. Summary

For the past decade, there has been a lot of interest in the use of ruthenium(II) catalysts for the catalytic functionalisation of sp^2 C-H bonds. These catalysts are relatively inexpensive, in comparison with rhodium and palladium catalysts and some work has demonstrated the versatility of the ruthenium catalysts, performing C-H transformations in water and air.

There are still challenges to overcome, such as obtaining better control over the regioselectivity and provide access to complementary site selectivities such as *meta* or *para* substituted products. There is also a need to develop milder reaction conditions in an effort to achieve cleaner and more sustainable methods for performing these transformations.

1.3. References

1. C. G. Jia, T. Kitamura and Y. Fujiwara, *Acc. Chem. Res.*, 2001, **34**, 633-639.
2. J. A. Labinger and J. E. Bercaw, *Nature*, 2002, **417**, 507-514.
3. K. Godula and D. Sames, *Science*, 2006, **312**, 67-72.
4. F. Kakiuchi and N. Chatani, *Adv. Synth. Catal.*, 2003, **345**, 1077-1101.
5. T. Satoh and M. Miura, *Chem. Lett.*, 2007, **36**, 200-205.
6. L. C. Campeau and K. Fagnou, *Chem. Commun.*, 2006, 1253-1264.
7. I. V. Seregin and V. Gevorgyan, *Chem. Soc. Rev.*, 2007, **36**, 1173-1193.
8. J. C. Lewis, R. G. Bergman and J. A. Ellman, *Acc. Chem. Res.*, 2008, **41**, 1013-1025.
9. F. Kakiuchi and T. Kochi, *Synthesis*, 2008, 3013-3039.
10. B.-J. Li, S.-D. Yang and Z.-J. Shi, *Synlett*, 2008, 949-957.
11. X. Chen, K. M. Engle, D.-H. Wang and J.-Q. Yu, *Angew. Chem. Int. Ed.*, 2009, **48**, 5094-5115.
12. L. Ackermann, R. Vicente and A. R. Kapdi, *Angew. Chem. Int. Ed.*, 2009, **48**, 9792-9826.

13. O. Daugulis, H.-Q. Do and D. Shabashov, *Acc. Chem. Res.*, 2009, **42**, 1074-1086.
14. D. A. Colby, R. G. Bergman and J. A. Ellman, *Chem. Rev.*, 2010, **110**, 624-655.
15. R. Jazzar, J. Hitce, A. Renaudat, J. Sofack-Kreutzer and O. Baudoin, *Chem. Eur. J.*, 2010, **16**, 2654-2672.
16. C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Commun.*, 2010, **46**, 677-685.
17. K. M. Engle, T. S. Mei, M. Wasa and J. Q. Yu, *Acc. Chem. Res.*, 2012, **45**, 788-802.
18. J. Wencel-Delord, T. Droege, F. Liu and F. Glorius, *Chem. Soc. Rev.*, 2011, **40**, 4740-4761.
19. W. R. Gutekunst and P. S. Baran, *Chem. Soc. Rev.*, 2011, **40**, 1976-1991.
20. G. Rouquet and N. Chatani, *Angew. Chem. Int. Ed.*, 2013, **52**, 11726-11743.
21. S. J. Blanksby and G. B. Ellison, *Acc. Chem. Res.*, 2003, **36**, 255-263.
22. A. D. Ryabov, *Chem. Rev.*, 1990, **90**, 403-424.
23. V. Ritleng, C. Sirlin and M. Pfeffer, *Chem. Rev.*, 2002, **102**, 1731-1769.
24. L. Ackermann, *Chem. Rev.*, 2011, **111**, 1315-1345.
25. D. A. Colby, A. S. Tsai, R. G. Bergman and J. A. Ellman, *Acc. Chem. Res.*, 2012, **45**, 814-825.
26. S. R. Neufeldt and M. S. Sanford, *Acc. Chem. Res.*, 2012, **45**, 936-946.
27. P. B. Arockiam, C. Bruneau and P. H. Dixneuf, *Chem. Rev.*, 2012, **112**, 5879-5918.
28. D. H. Ess, W. A. Goddard and R. A. Periana, *Organometallics*, 2010, **29**, 6459-6472.
29. L. N. Lewis and J. F. Smith, *J. Am. Chem. Soc.*, 1986, **108**, 2728-2735.
30. S. Murai, F. Kakiuchi, S. Sekine, Y. Tanaka, A. Kamatani, M. Sonoda and N. Chatani, *Nature*, 1993, **366**, 529-531.
31. S. Murai, F. Kakiuchi, S. Sekine, Y. Tanaka, A. Kamatani, M. Sonoda and N. Chatani, *Pure Appl. Chem.*, 1994, **66**, 1527-1534.
32. M. Sonoda, F. Kakiuchi, N. Chatani and S. Murai, *J. Organomet. Chem.*, 1995, **504**, 151-152.
33. M. F. Mcguiggan and L. H. Pignolet, *Inorg. Chem.*, 1982, **21**, 2523-2526.
34. R. J. Mckinney, G. Firestein and H. D. Kaesz, *Inorg. Chem.*, 1975, **14**, 2057-2061.
35. T. Matsubara, N. Koga, D. G. Musaev and K. Morokuma, *Organometallics*, 2000, **19**, 2318-2329.
36. C. P. Lenges and M. Brookhart, *J. Am. Chem. Soc.*, 1999, **121**, 6616-6623.
37. P. Lu, J. Paulasaari, K. Jin, R. Bau and W. P. Weber, *Organometallics*, 1998, **17**, 584-588.
38. H. Kawano, R. Tanaka, T. Fujikawa, K. Hiraki and M. Onishi, *Chem. Lett.*, 1999, 401-402.
39. F. Kakiuchi, T. Kochi, E. Mizushima and S. Murai, *J. Am. Chem. Soc.*, 2010, **132**, 17741-17750.
40. F. Kakiuchi, H. Ohtaki, M. Sonoda, N. Chatani and S. Murai, *Chem. Lett.*, 2001, 918-919.
41. M. Sonoda, F. Kakiuchi, A. Kamatani, N. Chatani and S. Murai, *Chem. Lett.*, 1996, 109-110.
42. F. Kakiuchi, M. Sonoda, T. Tsujimoto, N. Chatani and S. Murai, *Chem. Lett.*, 1999, 1083-1084.
43. B. M. Trost, K. Imi and I. W. Davies, *J. Am. Chem. Soc.*, 1995, **117**, 5371-5372.
44. F. Kakiuchi, Y. Tanaka, T. Sato, N. Chatani and S. Murai, *Chem. Lett.*, 1995, 679-680.
45. F. Kakiuchi, Y. Yamamoto, N. Chatani and S. Murai, *Chem. Lett.*, 1995, 681-682.
46. F. Kakiuchi, T. Uetsuhara, Y. Tanaka, N. Chatani and S. Murai, *Journal of Molecular Catalysis a-Chemical*, 2002, **182**, 511-514.
47. F. Kakiuchi, M. Yamauchi, N. Chatani and S. Murai, *Chem. Lett.*, 1996, 111-112.
48. F. Kakiuchi, T. Sato, M. Yamauchi, N. Chatani and S. Murai, *Chem. Lett.*, 1999, 19-20.
49. F. Kakiuchi, T. Sato, T. Tsujimoto, M. Yamauchi, N. Chatani and S. Murai, *Chem. Lett.*, 1998, 1053-1054.
50. F. Kakiuchi, M. Matsumoto, M. Sonoda, T. Fukuyama, N. Chatani, S. Murai, N. Furukawa and Y. Seki, *Chem. Lett.*, 2000, 750-751.
51. F. Kakiuchi, K. Igi, M. Matsumoto, T. Hayamizu, N. Chatani and S. Murai, *Chem. Lett.*, 2002, 396-397.
52. E. J. Moore, W. R. Pretzer, T. J. Oconnell, J. Harris, L. Labounty, L. Chou and S. S. Grimmer, *J. Am. Chem. Soc.*, 1992, **114**, 5888-5890.

53. N. Chatani, T. Asaumi, T. Ikeda, S. Yorimitsu, Y. Ishii, F. Kakiuchi and S. Murai, *J. Am. Chem. Soc.*, 2000, **122**, 12882-12883.
54. N. Chatani, T. Fukuyama, F. Kakiuchi and S. Murai, *J. Am. Chem. Soc.*, 1996, **118**, 493-494.
55. N. Chatani, Y. Ie, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 1997, **62**, 2604-2610.
56. N. Chatani, Y. Ishii, Y. Ie, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 1998, **63**, 5129-5136.
57. Y. Ie, N. Chatani, T. Ogo, D. R. Marshall, T. Fukuyama, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2000, **65**, 1475-1488.
58. N. Chatani, T. Fukuyama, H. Tatamidani, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2000, **65**, 4039-4047.
59. N. Chatani, S. Yorimitsu, T. Asaumi, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2002, **67**, 7557-7560.
60. T. Asaumi, N. Chatani, T. Matsuo, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2003, **68**, 7538-7540.
61. T. Fukuyama, N. Chatani, J. Tatsumi, F. Kakiuchi and S. Murai, *J. Am. Chem. Soc.*, 1998, **120**, 11522-11523.
62. S. Inoue, H. Shiota, Y. Fukumoto and N. Chatani, *J. Am. Chem. Soc.*, 2009, **131**, 6898-6899.
63. K. Shibata, N. Hasegawa, Y. Fukumoto and N. Chatani, *Chemcatchem*, 2012, **4**, 1733-1736.
64. N. Hasegawa, V. Charra, S. Inoue, Y. Fukumoto and N. Chatani, *J. Am. Chem. Soc.*, 2011, **133**, 8070-8073.
65. F. Kakiuchi, K. Igi, M. Matsumoto, N. Chatani and S. Murai, *Chem. Lett.*, 2001, 422-423.
66. F. Kakiuchi, S. Kan, K. Igi, N. Chatani and S. Murai, *J. Am. Chem. Soc.*, 2003, **125**, 1698-1699.
67. F. Kakiuchi, Y. Matsuura, S. Kan and N. Chatani, *J. Am. Chem. Soc.*, 2005, **127**, 5936-5945.
68. S. Ueno, N. Chatani and F. Kakiuchi, *J. Org. Chem.*, 2007, **72**, 3600-3602.
69. S. Hiroshima, D. Matsumura, T. Kochi and F. Kakiuchi, *Org. Lett.*, 2010, **12**, 5318-5321.
70. R. K. Chinnagolla and M. Jeganmohan, *Org. Lett.*, 2012, **14**, 5246-5249.
71. R. K. Chinnagolla and M. Jeganmohan, *Chem. Commun.*, 2014, **50**, 2442-2444.
72. L. H. Wang and L. Ackermann, *Chem. Commun.*, 2014, **50**, 1083-1085.
73. S. Oi, S. Fukita, N. Hirata, N. Watanuki, S. Miyano and Y. Inoue, *Org. Lett.*, 2001, **3**, 2579-2581.
74. S. Oi, Y. Ogino, S. Fukita and Y. Inoue, *Org. Lett.*, 2002, **4**, 1783-1785.
75. S. Oi, K. Sakai and Y. Inoue, *Org. Lett.*, 2005, **7**, 4009-4011.
76. S. Oi, E. Aizawa, Y. Ogino and Y. Inoue, *J. Org. Chem.*, 2005, **70**, 3113-3119.
77. S. Oi, R. Funayama, T. Hattori and Y. Inoue, *Tetrahedron*, 2008, **64**, 6051-6059.
78. S. Oi, H. Sasamoto, R. Funayama and Y. Inoue, *Chem. Lett.*, 2008, **37**, 994-995.
79. L. Ackermann, *Org. Lett.*, 2005, **7**, 3123-3125.
80. I. Ozdemir, S. Demir, B. Cetinkaya, C. Gourlaouen, F. Maseras, C. Bruneau and P. H. Dixneuf, *J. Am. Chem. Soc.*, 2008, **130**, 1156-1157.
81. L. Ackermann, A. Althammer and R. Born, *Angew. Chem. Int. Ed.*, 2006, **45**, 2619-2622.
82. L. Ackermann and M. Mulzer, *Org. Lett.*, 2008, **10**, 5043-5045.
83. L. Ackermann, J. Pospech and H. K. Potukuchi, *Org. Lett.*, 2012, **14**, 2146-2149.
84. M. K. Lakshman, A. C. Deb, R. R. Chamala, P. Pradhan and R. Pratap, *Angew. Chem. Int. Ed.*, 2011, **50**, 11400-11404.
85. L. Ackermann, A. Althammer and R. Born, *Tetrahedron*, 2008, **64**, 6115-6124.
86. X. Guo, G. Deng and C.-J. Li, *Adv. Synth. Catal.*, 2009, **351**, 2071-2074.
87. L. Ackermann, P. Novak, R. Vicente, V. Pirovano and H. K. Potukuchi, *Synthesis*, 2010, 2245-2253.
88. G. Rouquet and N. Chatani, *Chem. Sci.*, 2013, **4**, 2201-2208.
89. L. Ackermann, P. Novak, R. Vicente and N. Hofmann, *Angew. Chem. Int. Ed.*, 2009, **48**, 6045-6048.
90. S. I. Kozhushkov, D. S. Yufit and L. Ackermann, *Org. Lett.*, 2008, **10**, 3409-3412.
91. M. Schinkel, J. Wallbaum, S. I. Kozhushkov, I. Marek and L. Ackermann, *Org. Lett.*, 2013, **15**, 4482-4484.

92. M. Schinkel, I. Marek and L. Ackermann, *Angew. Chem. Int. Ed.*, 2013, **52**, 3977-3980.
93. J. Qi, L. B. Huang, Z. Y. Wang and H. F. Jiang, *Org. Biomol. Chem.*, 2013, **11**, 8009-8013.
94. S. I. Kozhushkov and L. Ackermann, *Chem. Sci.*, 2013, **4**, 886-896.
95. Y. Hashimoto, K. Hirano, T. Satoh, F. Kakiuchi and M. Miura, *Org. Lett.*, 2012, **14**, 2058-2061.
96. Y. Hashimoto, K. Hirano, T. Satoh, F. Kakiuchi and M. Miura, *J. Org. Chem.*, 2013, **78**, 638-646.
97. M. Itoh, Y. Hashimoto, K. Hirano, T. Satoh and M. Miura, *J. Org. Chem.*, 2013, **78**, 8098-8104.
98. C. Suzuki, K. Hirano, T. Satoh and M. Miura, *Org. Lett.*, 2013, **15**, 3990-3993.
99. R. Manikandan and M. Jeganmohan, *Org. Lett.*, 2014, **16**, 912-915.
100. L. Ackermann, *Acc. Chem. Res.*, 2014, **47**, 281-295.
101. L. H. Wang and L. Ackermann, *Org. Lett.*, 2013, **15**, 176-179.
102. L. Ackermann, A. V. Lygin and N. Hofmann, *Angew. Chem. Int. Ed.*, 2011, **50**, 6379-6382.
103. L. Ackermann and S. Fenner, *Org. Lett.*, 2011, **13**, 6548-6551.
104. B. Li, H. L. Feng, S. S. Xu and B. Q. Wang, *Chem. Eur. J.*, 2011, **17**, 12573-12577.
105. M. C. Reddy, R. Manikandan and M. Jeganmohan, *Chem. Commun.*, 2013, **49**, 6060-6062.
106. L. Ackermann, A. V. Lygin and N. Hofmann, *Org. Lett.*, 2011, **13**, 3278-3281.
107. Y. Su, M. A. Zhao, K. L. Han, G. Y. Song and X. W. Li, *Org. Lett.*, 2010, **12**, 5462-5465.
108. W. Ma, K. Graczyk and L. Ackermann, *Org. Lett.*, 2012, **14**, 6318-6321.
109. C. S. Yi and D. W. Lee, *Organometallics*, 2010, **29**, 1883-1885.
110. C. S. Yi and D. W. Lee, *Organometallics*, 2009, **28**, 4266-4268.
111. K.-H. Kwon, D. W. Lee and C. S. Yi, *Organometallics*, 2010, **29**, 5748-5750.
112. P. B. Arockiam, C. Fischmeister, C. Bruneau and P. H. Dixneuf, *Green Chem.*, 2011, **13**, 3075-3078.
113. Y. Hashimoto, T. Ueyama, T. Fukutani, K. Hirano, T. Satoh and M. Miura, *Chem. Lett.*, 2011, **40**, 1165-1166.
114. K. Padala and M. Jeganmohan, *Org. Lett.*, 2011, **13**, 6144-6147.
115. V. Lanke and K. R. Prabhu, *Org. Lett.*, 2013, **15**, 2818-2821.
116. K. Graczyk, W. B. Ma and L. Ackermann, *Org. Lett.*, 2012, **14**, 4110-4113.
117. K. Padala and M. Jeganmohan, *Org. Lett.*, 2012, **14**, 1134-1137.
118. V. Lanke and K. R. Prabhu, *Org. Lett.*, 2013, **15**, 6262-6265.
119. T. Ueyama, S. Mochida, T. Fukutani, K. Hirano, T. Satoh and M. Miura, *Org. Lett.*, 2011, **13**, 706-708.
120. L. Ackermann, L. Wang, R. Wolfram and A. V. Lygin, *Org. Lett.*, 2012, **14**, 728-731.
121. J. Li, C. Kornhaass and L. Ackermann, *Chem. Commun.*, 2012, **48**, 11343-11345.
122. M. C. Reddy and M. Jeganmohan, *Eur. J. Org. Chem.*, 2013, 1150-1157.
123. B. Li, J. Ma, Y. Liang, N. Wang, S. Xu, H. Song and B. Wang, *Eur. J. Org. Chem.*, 2013, 1950-1962.
124. W. Ma and L. Ackermann, *Chem. Eur. J.*, 2013, **19**, 13925-13928.
125. S. Oi, Y. Tanaka and Y. Inoue, *Organometallics*, 2006, **25**, 4773-4778.
126. Y. Ano, M. Tobisu and N. Chatani, *Synlett*, 2012, 2763-2767.
127. V. S. Thirunavukkarasu, S. I. Kozhushkov and L. Ackermann, *Chem. Commun.*, 2014, **50**, 29-39.
128. W. G. Shou, J. A. Li, T. X. Guo, Z. Y. Lin and G. C. Jia, *Organometallics*, 2009, **28**, 6847-6854.
129. M. Shang, S.-H. Zeng, S.-Z. Sun, H.-X. Dai and J.-Q. Yu, *Org. Lett.*, 2013, **15**, 5286-5289.
130. M. R. Yadav, R. K. Rit and A. K. Sahoo, *Org. Lett.*, 2013, **15**, 1638-1641.
131. M. Bhanuchandra, M. R. Yadav, R. K. Rit, M. R. Kuram and A. K. Sahoo, *Chem. Commun.*, 2013, **49**, 5225-5227.
132. V. S. Thirunavukkarasu, K. Raghuvanshi and L. Ackermann, *Org. Lett.*, 2013, **15**, 3286-3289.
133. J. Kim, J. Kim and S. Chang, *Chem. Eur. J.*, 2013, **19**, 7328-7333.
134. Q.-Z. Zheng, Y.-F. Liang, C. Qin and N. Jiao, *Chem. Commun.*, 2013, **49**, 5654-5656.

135. W. P. Liu and L. Ackermann, *Chem. Commun.*, 2014, **50**, 1878-1881.
136. Y. Q. Yang, Y. Lin and Y. Rao, *Org. Lett.*, 2012, **14**, 2874-2877.
137. G. Shan, X. S. Han, Y. Lin, S. Y. Yu and Y. Rao, *Org. Biomol. Chem.*, 2013, **11**, 2318-2322.
138. X. L. Yang, G. Shan and Y. Rao, *Org. Lett.*, 2013, **15**, 2334-2337.
139. V. S. Thirunavukkarasu, J. Hubrich and L. Ackermann, *Org. Lett.*, 2012, **14**, 4210-4213.
140. V. S. Thirunavukkarasu and L. Ackermann, *Org. Lett.*, 2012, **14**, 6206-6209.
141. W. Liu and L. Ackermann, *Org. Lett.*, 2013, **15**, 3484-3486.
142. F. Z. Yang and L. Ackermann, *Org. Lett.*, 2013, **15**, 718-720.
143. K. Padala and M. Jeganmohan, *Chem. Commun.*, 2013, **49**, 9651-9653.
144. A. Tlili, J. Schranck, J. Pospech, H. Neumann and M. Beller, *Angew. Chem. Int. Ed.*, 2013, **52**, 6293-6297.
145. K. Inamoto, J. Kadokawa and Y. Kondo, *Org. Lett.*, 2013, **15**, 3962-3965.
146. T. Kochi, S. Urano, H. Seki, E. Mizushima, M. Sato and F. Kakiuchi, *J. Am. Chem. Soc.*, 2009, **131**, 2792-2793.
147. T. Kochi, A. Tazawa, K. Honda and F. Kakiuchi, *Chem. Lett.*, 2011, **40**, 1018-1020.
148. R. K. Chinnagolla, S. Pimparkar and M. Jeganmohan, *Chem. Commun.*, 2013, **49**, 3146-3148.

Chapter 2. *Meta*-C-H Sulfonation of Heteroaromatics

2.1. *Meta*-C-H functionalisation of aromatics

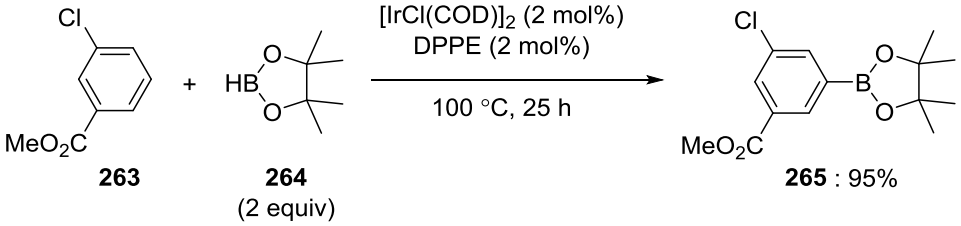
For the past decade, catalytic C-H functionalisation methodologies have undergone rapid development, in particular for the modification of aromatics.[1-4] This synthetic strategy provides an alternative route to the traditional electrophilic aromatic substitutions such as Friedel-Crafts reactions. In Friedel-Crafts reactions, it is known that electron-donating substituents direct the incoming electrophiles to the *ortho* and *para* positions, whereas electron-withdrawing groups lead to *meta*-functionalisation. This means that functional groups have to be pre-installed beforehand for the products to achieve the desired regioselectivity. Moreover, substrates with electron-donating groups cannot undergo *meta*-functionalisation because of their inherent electronic characteristics, the substitution will be directed to the *ortho* or *para* positions. Beside the issues with regioselectivity, reactions such as Friedel-Crafts acylations require the use of stoichiometric amounts of Lewis acids and some of the Lewis acids used are toxic such as $SnCl_4$. The issue with regioselectivity have been addressed with the use of catalytic amounts of transition-metals to perform the C-H functionalisation of arenes. The transition-metal activates the C-H bond, which makes it more reactive towards elctrophiles to form a new functionalised bond. At present, many methods use transition-metal catalysts to transform aromatic sp^2 C-H bonds to provide *ortho*-substituted products through functional group directed cyclometallation. While the number of available methods for *ortho*-C-H functionalisation has risen dramatically, methods that produce the *meta*-functionalised aromatic product are much less common.[5, 6]

2.1.1. *Meta*-sp^2 C-H functionalisation *via steric* control

Both Hartwig *et al*. and Smith *et al*. have both independently reported the one-pot functionalisation of the *meta* position of arenes *via* iridium-catalysed C-H borylation (Scheme 94). Smith *et al*. described the *meta*-selective synthesis of boronic esters, whereas Hartwig *et al*. performed a sequential reaction of C-H borylation followed by halogenation.[7,8] The *meta*-selectivity results from steric interactions, with both electron-rich and electron-poor arenes giving similar yields and selectivity. Functional groups such as nitriles, esters, amides and protected alcohols as well as heteroarene such as pyridine were tolerated in the reaction. Recently, Robbins

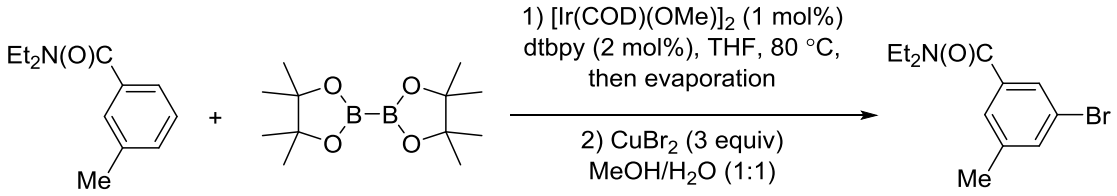
and Hartwig have utilised the *meta*-borylated products in Suzuki-Miyaura coupling to afford *meta*-alkylated arenes as products.[9]

Smith *et al.* (2002)



263 **264** (2 equiv) **265** : 95%

Hartwig *et al.* (2007)

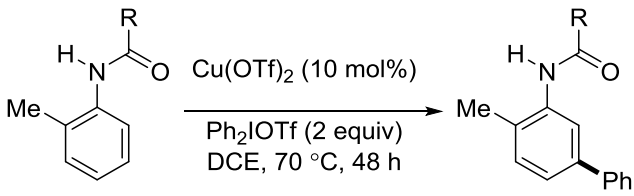


266 **267** (1 equiv) **268** : 80%

Scheme 94

2.1.2. *Meta*-sp^2 C-H functionalisation *via* catalyst control

In 2009, Phipps and Gaunt reported a copper-catalysed arylation of electron-rich anilides.[10] The *meta*-selectivity violates the traditional rule that anilides favour electrophilic aromatic substitution at the *ortho* or *para* position. The acyl R group has a major influence on the yield as shown in Scheme 95, the more bulky the R group is, the higher the product yield. For example the treatment of 2-methylpivanilide **269e** with Ph_2IOTf in the presence of 10 mol% of $Cu(OTf)_2$ in DCE at 70 °C afforded the *meta*-arylated product **270e** in 79% yield.

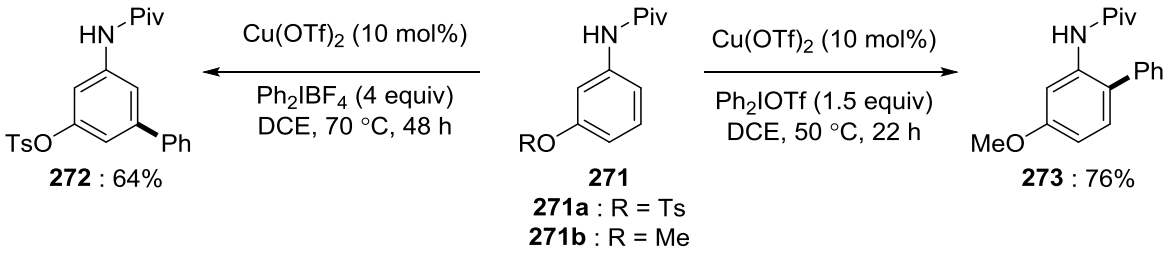


269a : R = Me
269b : R = OMe
269c : R = NEt_2
269d : R = Ph
269e : R = ^{t}Bu

270a : R = Me : 43%
270b : R = OMe : 45%
270c : R = NEt_2 : 31%
270d : R = Ph : 73%
270e : R = ^{t}Bu : 79%

Scheme 95

The mild copper catalysed arylation is compatible with a range of functional groups. Both electron-donating and electron-withdrawing substituted anilides undergo arylation and give the *meta*-arylated products exclusively; although electron-deficient substrates suffer from poorer reactivity. Interestingly, the chemoselectivity of 3-oxygenated pivanilide **271** can be tuned by manipulating the hydroxyl protecting group. For example, 3-OTs group **271a** facilitates reaction in the *meta*-position to the amide; in contrast, for a substrate containing a 3-OMe **271b** substituent, arylation takes place on the *ortho* site (Scheme 96).



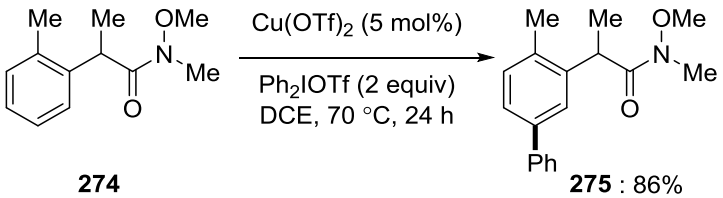
272 : 64%

271
271a : R = Ts
271b : R = Me

273 : 76%

Scheme 96

Gaunt extended the *meta*-functionalisation process to α-aryl carbonyl compounds where Weinreb amides were found to be the best substrates for the catalyst system (Scheme 97).[11] Various symmetrical and unsymmetrical diaryl iodonium triflates reacted with the Weinreb amides and delivered the *meta*-arylated product in moderate to good yields. Nevertheless, it is worth noting that electron-deficient Weinreb amides were not examined in this study, which suggests the reaction may be limited to electron-neutral and electron-rich substrates only. Interestingly, the *meta*-arylation can also take place in the absence of the copper catalyst but the reaction only proceeds at a narrow threshold temperature range of 80 – 90 °C.

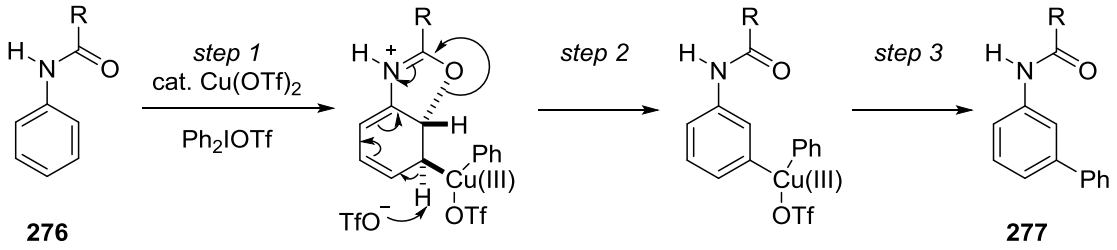


274

275 : 86%

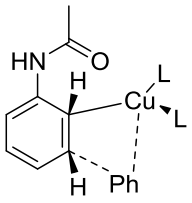
Scheme 97

Gaunt *et al.* proposed an anti-oxycupration mechanism involving a Cu(III) aryl species to explain the *meta*-selectivity (Scheme 98).



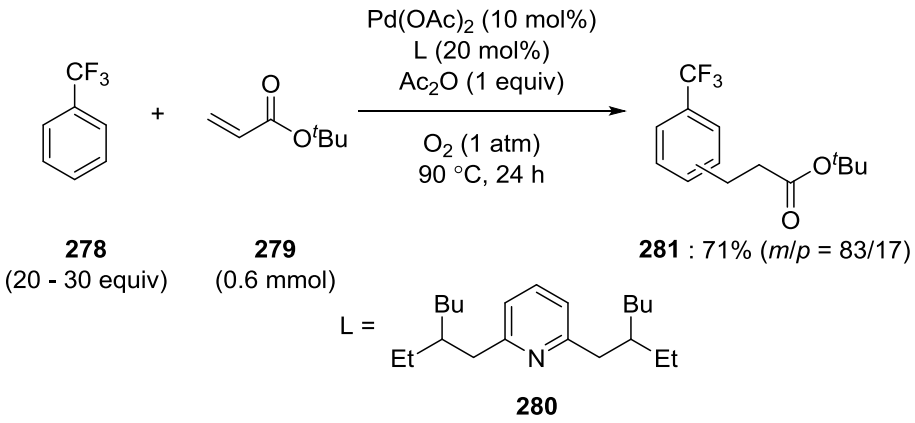
Scheme 98

However in 2011, a DFT study by Wu *et al.* disagreed with Gaunt's proposed mechanism of the copper(II) catalysed *meta*-arylation of anilides. DFT calculations revealed the anti-oxycupration transition state is 50.7 kcalmol^{-1}, which is a high energy barrier to overcome indicating an unfavourable pathway.[12] DFT calculations on other possible mechanistic pathways, suggested the *meta*-selectivity is most likely *via* a Heck-like four-membered ring transition state through a Cu(II)-Ph intermediate (Scheme 99). The *ortho*-phenyl intermediate has a slightly longer C_{ortho}-Cu bond distance (2.031 Å) than the transition state intermediate (2.008 Å), signifying the C_{ortho}-Cu bond breaks and Cu(III) is reduced to Cu(I). Then the aromatic ring is rearomatised *via* proton abstraction of the *meta*-proton by the free OTf anion. It is noteworthy that a concerted-metallation deprotonation (CMD) mechanism is kinetically plausible as well.[13]



Scheme 99

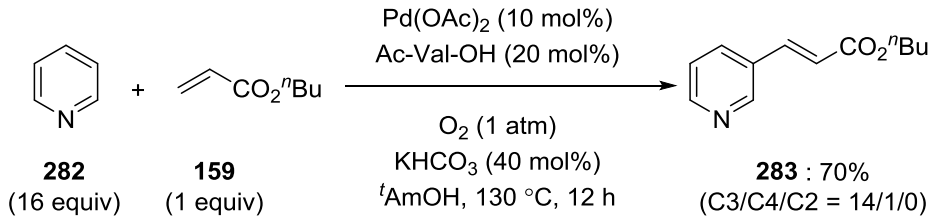
Yu *et al*. studied the *meta*-C-H olefination of electron deficient arenes with olefins using palladium catalysis with the aid of pyridine ligands (Scheme 100).[14] Clever design of 2,4-dialkyl pyridine ligands that would coordinate with Pd(II) however not bind too strongly, 2,6-disubstituted ligand **280** was employed as the ligand of choice. Ligand **280** can strongly coordinate to the Pd(II) centre in a monodentate fashion to allow C-H activation to take place and it has enough steric bulk to perform the olefination reaction. A range of electron-deficient arenes reacted with olefins such as acrylates or cinnamate substrates and obtained the olefinated arenes in good yields with the *meta*-olefinated arenes as the major product and a small amount of *para*-olefinated products were also produced.



Scheme 100

Zhang and co-workers performed DFT calculations to gain insights into the mechanism.[15] The most favourable reaction pathway involves an initial CMD mechanism for the aromatic C-H activation, followed by substitution of the pyridine ligand by the olefin. The alkene is then activated through the alkene double bond into the Pd(II)-aryl bond. The rate-determining step was calculated as the CMD step which features as a six-membered ring transition state to form a Pd(II)-aryl intermediate. In addition, the regioselectivity of the product is determined by the steric repulsion effect of the ancillary pyridine ligand with OAc ligands on the palladium centre, it prevents the olefination on the *ortho*-position. As for the *meta*/*para*-selectivity, this is due to a minor electronic effect of the preinstalled substituent on the benzene ring on the cleaving C-H bond, which leads to a mixture of *meta*- and *para*-olefinated products.

A similar study to Yu's work was reported by Zeng and co-workers, utilising mono-*N*-protected amino acid, Ac-Val-OH or Ac-Ile-OH, as ligands for the palladium-catalysed *meta*-arylation of pyridines and electron-deficient arenes.[16] Reaction of pyridine **282** with *n*-butyl acrylate **159** in the presence of 10 mol% of $Pd(OAc)_2$, 20 mol% of Ac-Val-OH, molecular oxygen (1 atm) as the oxidant, 40 mol% of potassium bicarbonate and *tert*-amyl alcohol as the reaction solvent and heated at 130 °C for 12 hours to afford C-3 selective alkenylpyridine **283** in good yield with high regioselectivity (Scheme 101). The advantage of this method is that the ligands used are inexpensive and readily available, in comparison to Yu's method the ligand has to be synthesised beforehand. However, it is noteworthy that Zeng's conditions are performed at a much higher temperature.

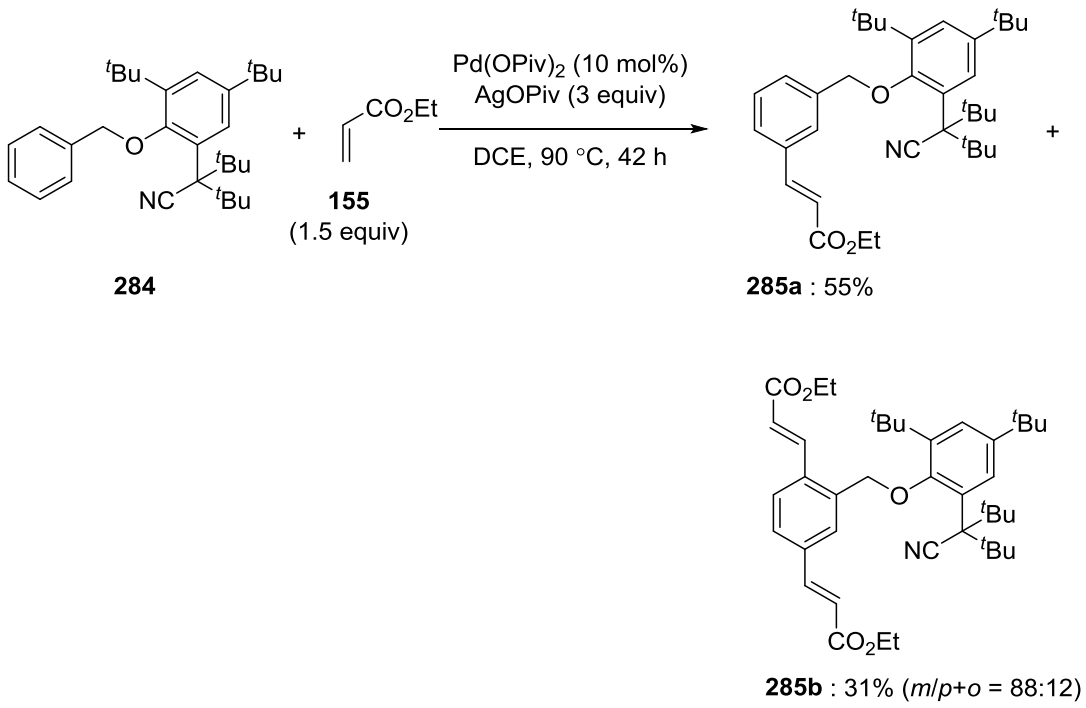


Scheme 101

2.1.3. *Meta-sp²* C-H functionalisation *via* end-on template

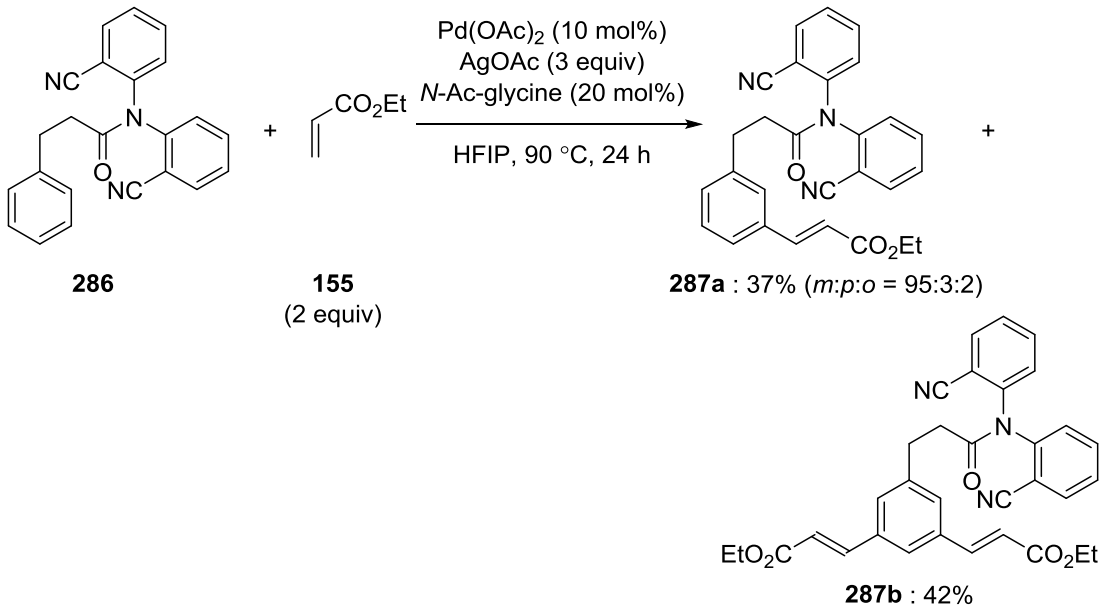
For the past few years, the use of an end-on template has emerged for functionalising remote *meta*-C-H bonds. In 2012, Yu *et al*. engineered a class of removable nitrile containing directing groups for the functionalisation of *meta*-C-H bonds of aromatic substrates *via* a cyclophane-type transition state.[17] The template utilises a nitrile group to coordinate to the Pd(II) centre in a linear fashion, directing the Pd to the *meta*-C-H bond.

Scheme 102 shows one of templates used in the *meta*-olefination. The template was designed to direct activation to the distal *meta*-C-H bond and the linear coordination of Pd to nitrile would prevent the Pd access to the *ortho*-C-H bonds and the flat arene is to ensure both the directing group and *meta*-C-H bond of the substrate are coplanar. In addition, the sterically bulky *tert*-butyl group plays an important role of directing the nitrile closer to the *meta*-C-H bond and it is placed on the α-position adjacent to the nitrile group, which increases the substrates' reactivity *via* the Thorpe-Ingold effect.[18-21]

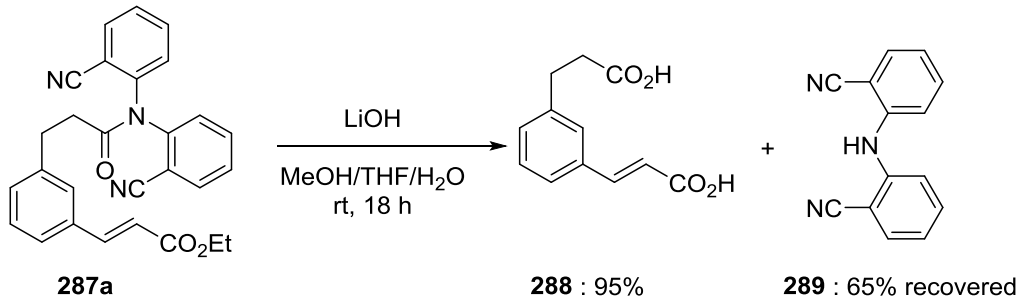


Scheme 102

Another nitrile-containing template was shown to be an effective directing group for *meta*-olefination of arenes, with high *meta*-selectivity (Scheme 103). The template assisted *meta*-C-H alkenylation can be used to functionalise substrates such as toluene derivatives, hydrocinnamic acids, 2-biphenylcarboxylic acids and unnatural amino acids. A broad range of olefins such as acrylates, divinylphosphonate, as well as di- and trisubstituted alkenes containing an ester substituent were all compatible in the reaction. The template **289** can be easily removed by hydrolysis at room temperature using LiOH as a base to give the corresponding carboxylic acid in high yield (Scheme 104).



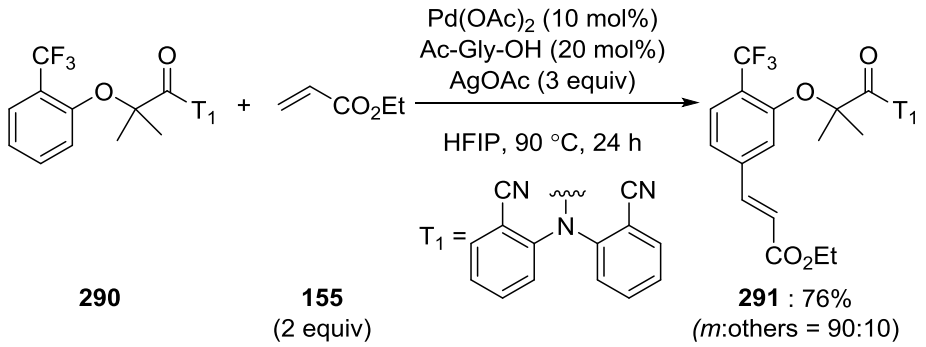
Scheme 103



Scheme 104

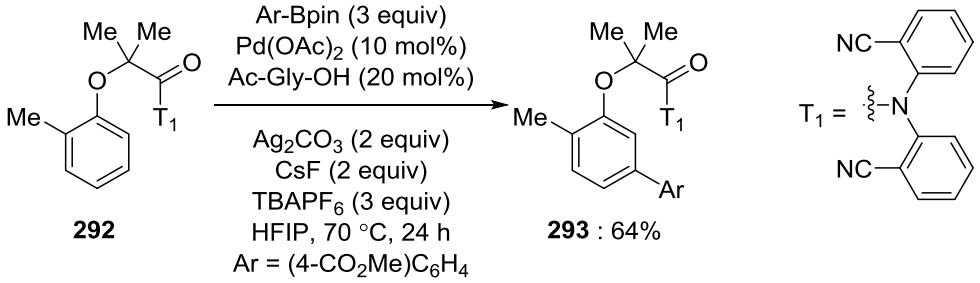
A DFT study by Houk *et al*. revealed the C-H activation step is most likely *via* a concerted metallation deprotonation mechanism involving a dimeric catalytic species.[22] It was indistinguishable as to which dimeric species was involved in the catalytic cycle, although both $Pd_2(OAc)_4$ and $PdAg(OAc)_3$ dimeric species can selectively activate the *meta* C-H bonds, contrary to the monomeric Pd mechanism, which favoured the activation of the *ortho* position. In addition, AgOAc demonstrated a dual role, functioning as both an oxidant and part of the heteronuclear active species in the mechanism.

Yu *et al*. have applied the nitrile template to α-phenoxylacetic acid **290** for performing *meta*-C-H olefination.[23] The *meta*-alkenylation complements the *ortho*- and *para*-electrophilic substitution, thus providing a novel strategy to construct densely functionalised arenes (Scheme 105).



Scheme 105

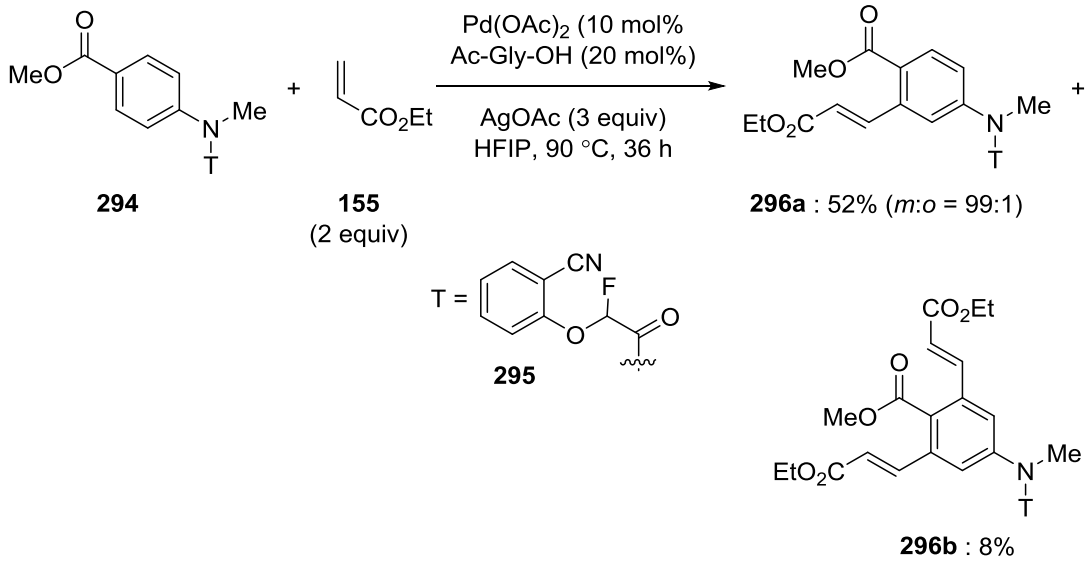
The Yu group have also designed a U-shaped nitrile template that was employed in the *meta*-arylation and methylation of 3-phenylpropanoic acid and phenolic derivatives (Scheme 106).[24] The combination of the weakly coordinating template and mono-protected amino acid ligand are essential for the cross-coupling of aromatic C-H bonds with the organoboron reagents. Furthermore, experimental and DFT calculations revealed that the formation of monomeric Pd(MPAA) complexes are involved in the catalytic cycle and that a novel type of CMD mechanism is involved, in which the MPAA participates in the deprotonation of the aromatic C-H bond.[25]



Scheme 106

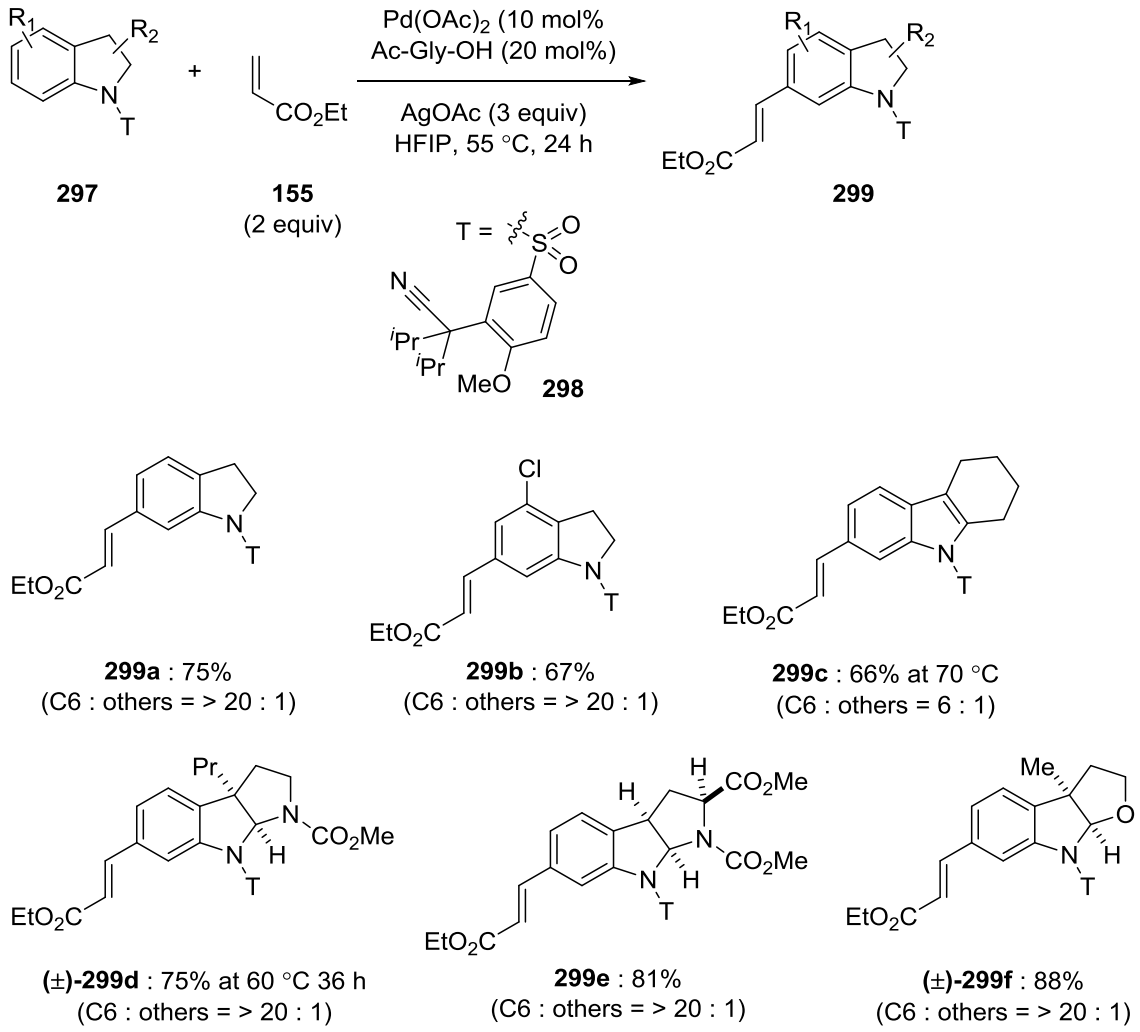
In 2014, Yu *et al*. developed a new template for performing olefination and acetoxylation of distal *meta*-C-H bonds of anilines and benzylic amines (Scheme 107).[26] Substrates such as tetrahydroquinolines, benzoxazines, anilines, benzylamines, 2-phenylpyrrolidines and 2-phenylpiperidines were all selectively functionalised at the *meta*-position. With this methodology, the authors proposed that the presence of a fluorine atom on the template provides

conformational bias to facilitate the remote *meta*-C-H olefination, and the ligand Ac-Gly-OH enhances the *meta*-selectivity even further.



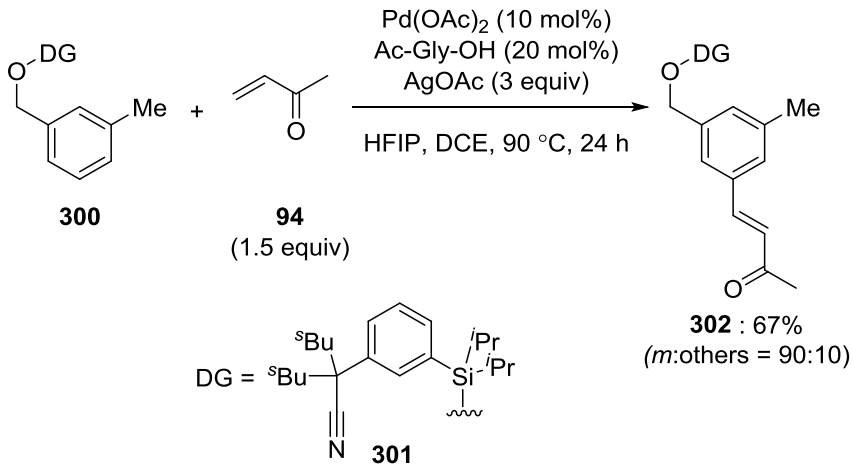
Scheme 107

Yu *et al.* have also recently reported *meta*-C-H functionalisation of indolines **297** using a nitrile template **298** which is attached at the indolinyl nitrogen *via* a sulfonamide linkage for directing the reaction to the distal *meta* position (C6).[27] The reaction is practical, as important structural motifs such as indoles, furoindoline, pyrroloindoline and tetrahydro-β-carboline were compatible for *meta*-C-H olefination and obtained the corresponding *meta*-olefinated products in good yields and high regioselectivity (Scheme 108).



Scheme 108

Tan *et al*.[28] have also adopted the concept of a weak coordinating nitrile directing group but using a silicon tether **301** rather than the carbon based tether that Yu *et al*. employs. Various benzyl alcohols with electron-donating or withdrawing substituents reacted efficiently with acrylates with high *meta* selectivity (Scheme 109).

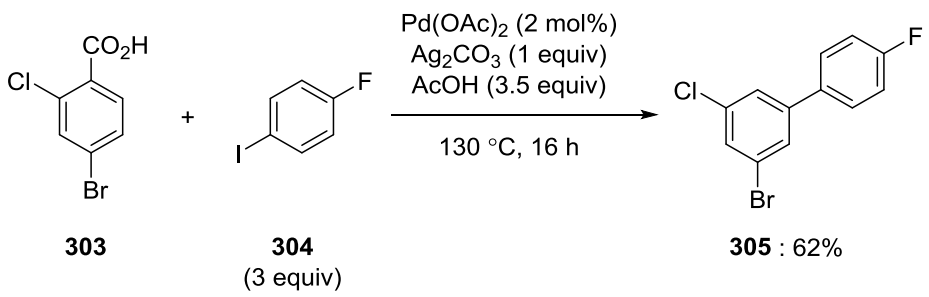


Scheme 109

The "end-on" coordinating strategy has provided a new platform to transform sp^2 C-H bonds however, it is worth noting that some of the templates are not commercially available and need to be synthesised beforehand. On the other hand, these removable auxiliaries can be recovered upon cleavage and can be recycled and reused.

2.1.4. Traceless directing group for *meta*-sp^2 C-H functionalisation

An alternative approach for accessing *meta*-functionalised arenes is by employing a carboxylic acid as a traceless directing group. Larrosa *et al*. utilised 2-substituted benzoic acids for performing the tandem Pd-catalysed direct arylation *ortho* to the carboxylic acid followed by protodecarboxylation to afford the pseudo *meta*-selective C-H arylated product.[29] A variety of electron-donating and electron-withdrawing substituents such as Cl, F, NO_2, CF_3 and OMe were all tolerated in the reaction (Scheme 110).

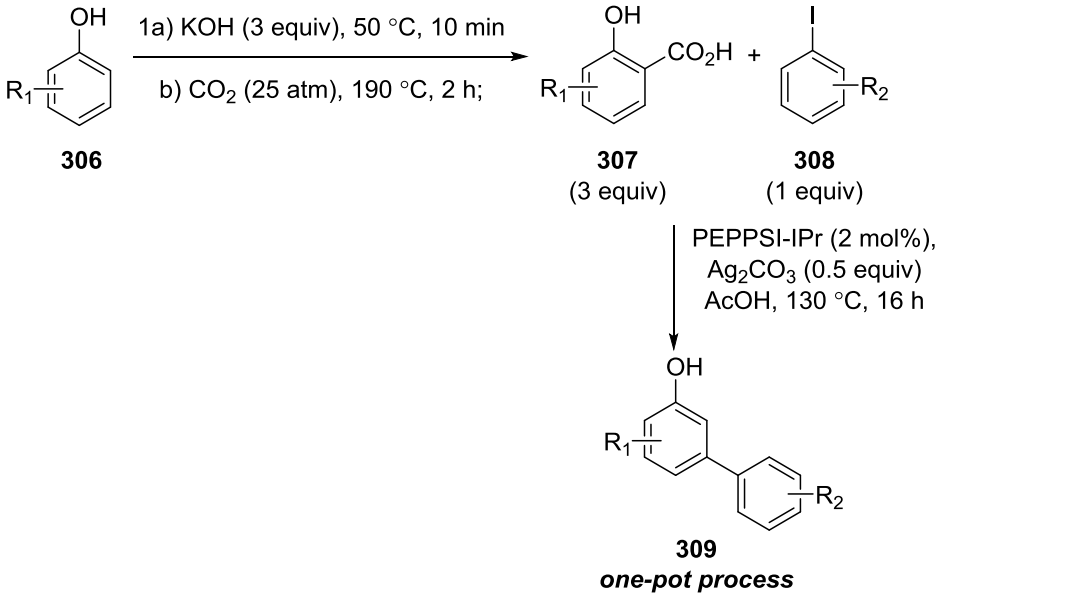


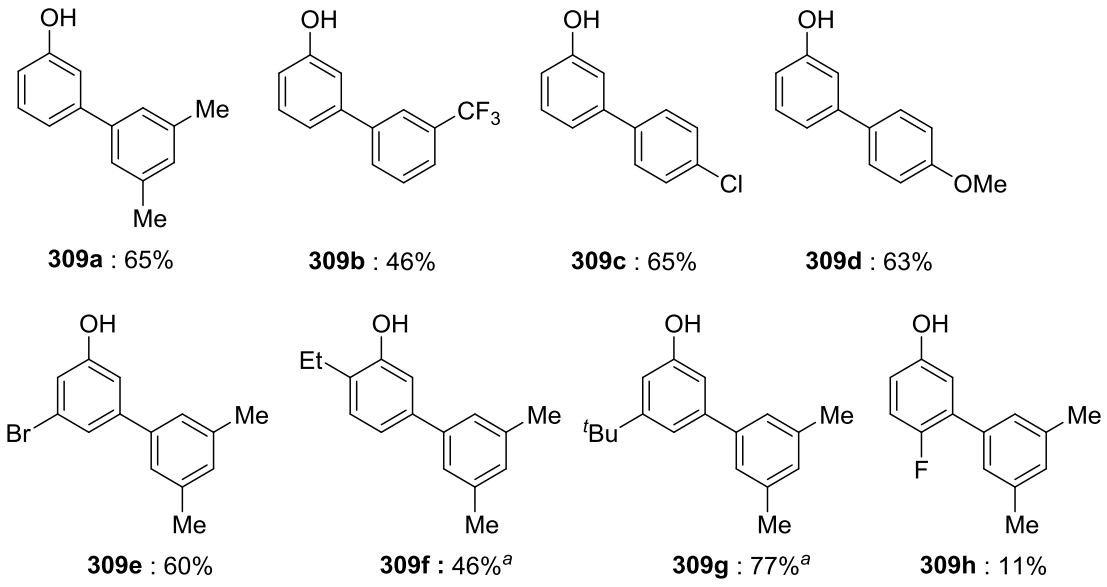
Scheme 110

This method is attractive, as the substrate, benzoic acids are cheap and readily available starting materials. More importantly, the directing group employed is a carboxylic acid, which can be easily installed by carboxylation with CO_2 and can be removed by decarboxylation; this is a valuable asset for the development of complex medicinal and biologically active compounds.

Very recently, Larrosa *et al.* extended their chemistry to phenols as substrates. The reaction is practical as it is also a one-pot process (Scheme 111).[30] Firstly the phenol undergoes *ortho*-carboxylation with CO_2 *via* the Kobe-Schmitt reaction, followed by coupling with aryl iodide in the presence of 2 mol% of PEPPSI-IPr and 0.5 equivalents of Ag_2CO_3 in AcOH at 130 °C to give the *meta*-arylated phenol as product. This reaction process encompasses three steps in one-pot involving carboxylation, arylation and decarboxylation as the overall sequence. The reaction is completely regioselective and no sign of the *ortho* and *para*-arylated products are detected. Furthermore, the reaction is completely selective for mono-arylation, which is rarely observed, as most C-H arylation reactions reported observe both the mono-and bisarylated products.[31]

The traceless directing group methodology for the *meta*-arylation of phenols has a broad reaction scope, in which a variety of electron-rich and electron-deficient iodoarenes were compatible coupling partners. Useful functional handles such as Cl and Br were tolerated in the reaction and could be used in further synthetic transformations. However, there is a drawback, *ortho*-substituted iodoarenes are not compatible coupling partners, and the authors suggested it is due to steric hindrance preventing the reaction from proceeding.



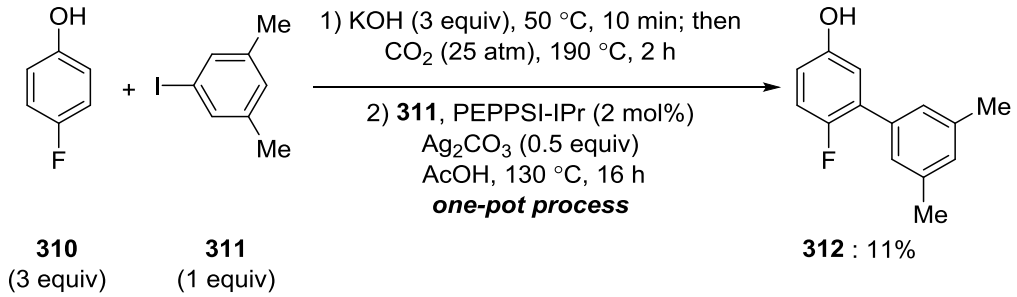


[a] 4 mol% of $Pd(OAc)_2$ was added in two batches, instead of PEPPSI-IPr & strirred for 40 h

Scheme 111

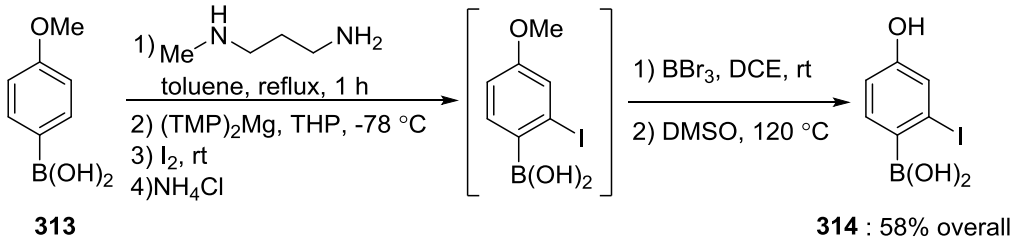
As for the substrate scope, a range of phenols proceeded in the reaction to afford the *meta*-arylated products, but with slight alterations to the reaction conditions. The catalyst was switched to $Pd(OAc)_2$ and the catalyst loading was also adjusted to 4 mol% and was added in two batches of 2 mol% loading during the reaction indicating that catalyst decomposition can impede the reaction for some substrates. *Para*-substituted phenols displayed poor reactivity, for example, *para*-fluorophenol **310** afforded the corresponding *meta*-arylated product **312** in only 11% yield and *para*-methylphenol led to no coupling (Scheme 112). From the results, it is clearly highlighted

that steric hindrance adjacent to the reacting C-H bond is detrimental to the reaction leading to the formation of a highly sterically encumbered intermediate.



Scheme 112

Cheon and co-workers have adopted the concept of using a traceless directing group for the functionalisation of phenols (Scheme 113).[32] However, it has many drawbacks; firstly, a removable directing group has to be installed prior to use in the synthesis. More importantly, the reaction takes 5 individual steps to obtain the *meta*-functionalised product, making it more time-consuming and impractical considering there is a lot of literature for performing C-H functionalisations in one step.

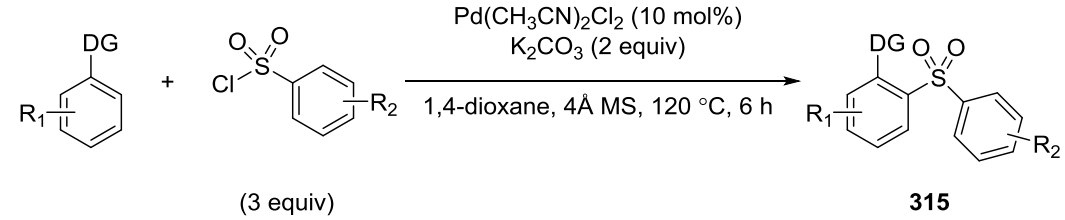


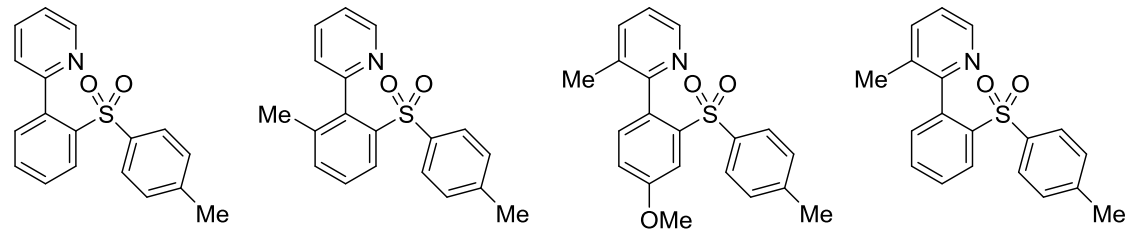
Scheme 113

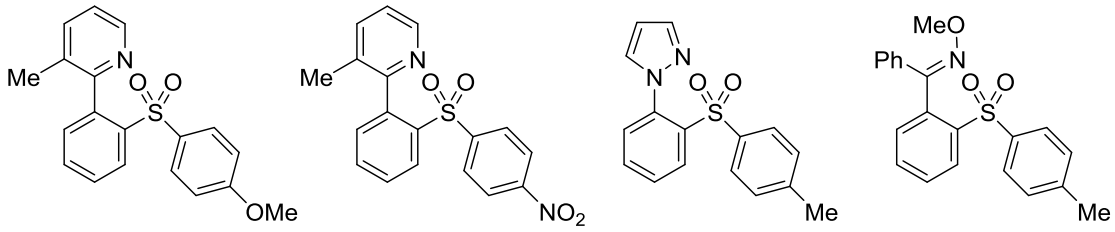
2.2.1. *Ortho*-C-H Sulfonation

In 2009 Dong and co-workers reported a palladium-catalysed arene sulfonation, in which the sulfonation is selectively directed to the *ortho* position (Scheme 114).[33] This methodology could prove to be useful for synthesising biologically important and medicinal targets, as sulfones are found in many drug molecules.[34-38]

The findings show that this reaction is influenced by steric factors, for example **315b** where a methyl group is situated on the *ortho* position of the aromatic ring, the product was obtained in 43% yield. In contrast, for **315d** the methyl substituent on the pyridine ring gave 88% yield. The electronic characteristics of the substrate had a significant impact on the yield of the product as electron poor sulfonyl chlorides were less efficient as coupling partners compared to the electron rich sulfonyl chlorides. For example, an electron-donating substituent such as OMe group gave the product **315e** in 83% yield, however when the substituent was replaced by an electron-withdrawing group, NO_2, afforded the product **315f** in 68% yield. Other directing groups such as pyrazoles and oximes can also undergo *ortho*-sulfonation with satisfactory yields.

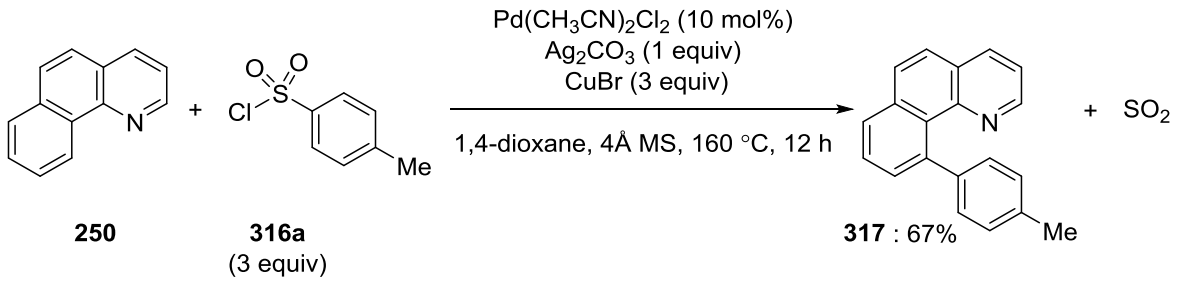






Scheme 114

Interestingly, at 160 °C, treatment of benzo[*h*]quinoline **250** with *para*-toluenesulfonyl chloride (*p*-TsCl) **309a**, gave an unexpected result and underwent a selective desulfinative cross-coupling. The observation illustrates the utility of sulfonyl chloride as oxidants for C-H bond functionalisation (Scheme 115).

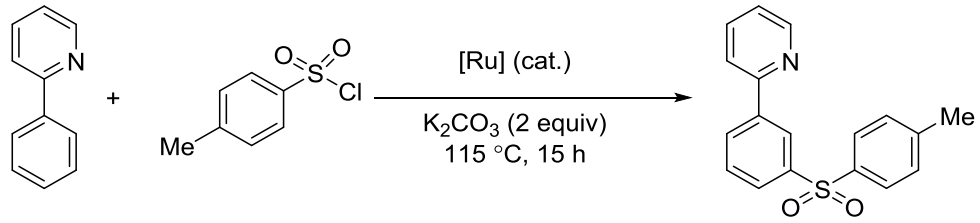


Scheme 115

2.2.2. *Meta*-C-H Sulfonation

Inspired by Dong's study on *ortho*-C-H sulfonation, work within the Frost group was directed towards the C-H sulfonation in the presence of other transition metal catalysts. Previous work from the group performed the C-H sulfonation in the presence of a ruthenium catalyst and found the C-H sulfonation is *meta* selective, with none of the *ortho*-product observed (Table 1, entry 1).[39] An initial optimisation was performed by Jameel Marafie, Dr Araminta E. W. Ledger and Dr Ourida Saidi (Table 1) and various ruthenium precatalysts were screened. It was found that $[RuCl_2(p\text{-cymene})]_2$ was the best catalyst and switching the solvent to acetonitrile (MeCN) provided the *meta*-sulfonated product **318a** in 80% isolated yield (Table 1, entry 11).

Table 1. Optimisation studies for the ruthenium-catalysed *meta*-sulfonation of 2-phenylpyrdine[39] carried out by Jameel Marafie, Dr Araminta E. W. Ledger and Dr Ourida Saidi

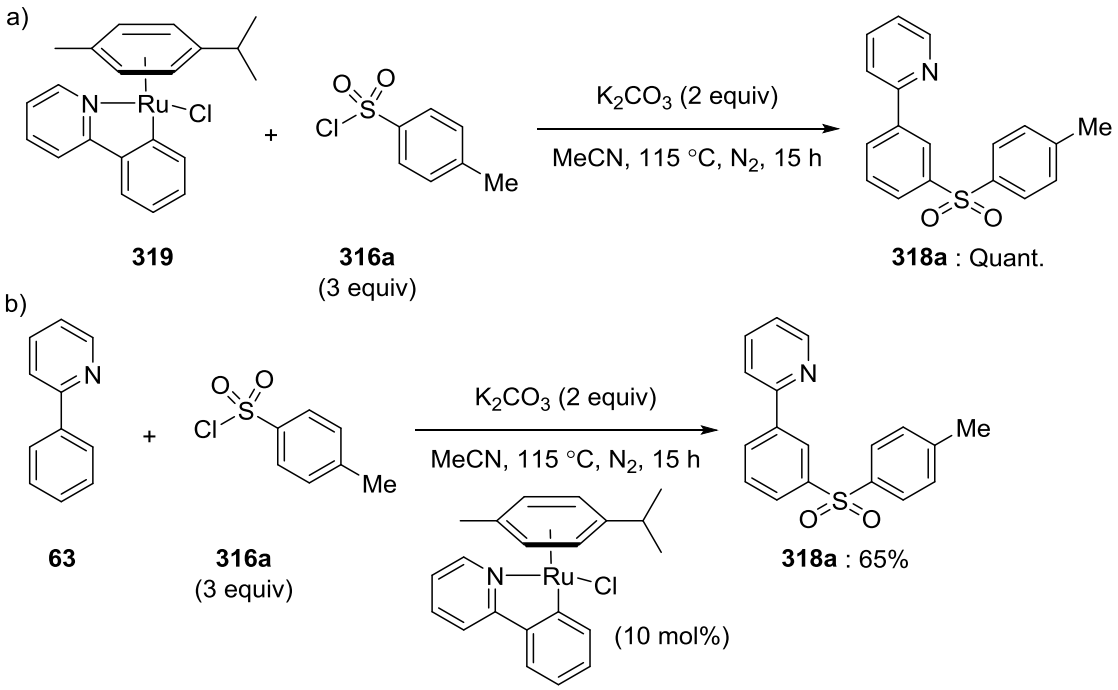


entry[a]	[Ru complex]	solvent	yield (%)[b]
1	$Ru(PPh_3)_3HCl$	dioxane	25
2	$Ru(dppf)(PPh_3)HCl$	dioxane	7
3	$Ru(xantphos)(PPh_3)HCl$	dioxane	trace

4	$Ru(PPh_3)_3(CO)H_2$	dioxane	8
5	$Ru_3(CO)_{12}$	dioxane	0
6	$[RuCl_2(p\text{-cymene})]_2$	dioxane	27
7	$[RuCl_2(p\text{-cymene})]_2$	EtOAc	24
8	$[RuCl_2(p\text{-cymene})]_2$	THF	28
9	$[RuCl_2(p\text{-cymene})]_2$	toluene	5
10	$[RuCl_2(p\text{-cymene})]_2$	MeCN	62
11	$[RuCl_2(p\text{-cymene})]_2$	MeCN	80[c]
12	-	MeCN	0
13	-	1,4-dioxane	0

[a]Reaction conditions: 2-phenylpyridne (1.0 mmol), *p*-TsCl (3.0 mmol), [Ru] catalyst (2.5 mol%), K_2CO_3 (2 equiv), solvent (3 mL), 115 °C, 15 h. [b]Isolated yields. [c]5 mol% $[RuCl_2(p\text{-cymene})]_2$

The switch in regioselectivity from Pd to Ru, suggests that these two reactions must follow different mechanistic pathways, to obtain the different regioselectivities. It was hypothesised that the chelating group facilitates the formation of a stable Ru-C_{aryl} σ-bond that induces a strong *para*-directing effect.[40, 41] The ruthenium centre functions as a directing group which directs the electrophilic aromatic substitution (S_EAr) on the position *para* to the ruthenium *via* inductive effects, followed by demetallation to provide the *meta*-sulfone product. To test this hypothesis, Dr Ourida Saidi employed the isolated complex **319** and treated it with 3 equivalents of *p*-TsCl **316a** under the standard conditions and afforded the *meta*-sulfonated product **318a** in quantitative yield (Scheme 116a). Also the complex **319** was employed as a catalyst (10 mol%) for the reaction of 2-phenylpyridine **63** with *p*-TsCl **316a** under the standard conditions and gave the corresponding *meta*-product **318a** in 65% isolated yield (Scheme 116b). From the observation it is evident that the complex **319** does indeed undergo demetallation and catalyst turnover was achieved, thereby it can be speculated that complex **319** is likely to be involved in the catalytic cycle.



Scheme 116

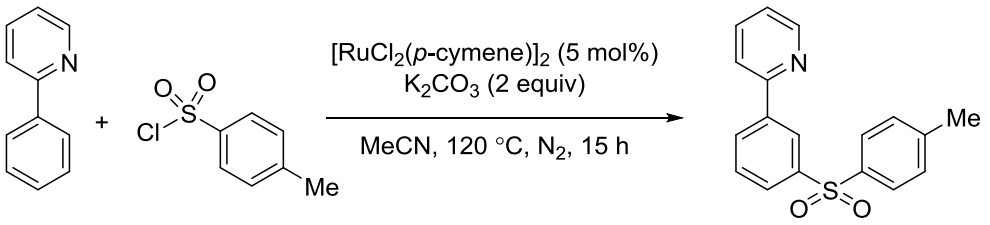
2.3. Aims and Objectives

The research in this thesis is focussed on developing novel ruthenium-catalysed C-H functionalisation reactions. The aims of this chapter are to further optimise this novel transformation and to explore the scope with other sulfonyl chlorides as well as extending the reaction to other substrates.

2.4. Results and Discussion

2.4.2a. *Meta*-C-H functionalisation of 2-phenylpyridine

The aim of investigations in this thesis was to develop novel ruthenium(II) catalysed C-H functionalisation reactions for heteroaromatics. As the *meta*-C-H sulfonation of 2-phenylpyridine developed in this group is the first example of catalytic *meta*-C-H sulfonation, it was decided to further optimise and explore the scope of this reaction. Firstly, the reaction of 2-phenylpyridine **63** with *p*-TsCl **316a** was attempted under the standard conditions, and afforded the *meta*-sulfonated 2-phenylpyridine **318a** in 32% isolated yield (Scheme 117). Unfortunately, after several attempts of repeating the reaction, the *meta*-product **318a** was obtained in approximately 30% yield each time. Therefore, further optimisations were performed to see if the reproducibility could be improved.

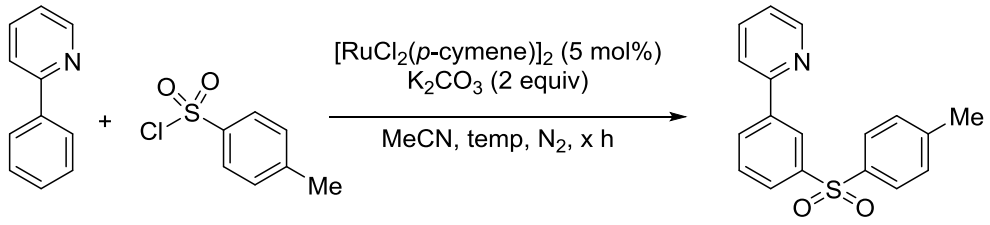


63 **316a** (3 equiv) **318a** : 32%

Scheme 117

The reaction time was extended to 20 hours and this made no difference to the product yield (Table 2, entry 1). The reaction temperature was examined, as the reaction temperature is considerably higher than the boiling point of acetonitrile, which is 82 °C, it would be interesting to see if the reaction will work at the boiling point of the solvent. The reaction was carried out at 90 °C for 20 hours and no product was formed in the reaction.

Table 2. Optimisation for the effect of temperature and reaction time on the *meta*-sulfonation



63 **316a** (3 equiv) **318a**

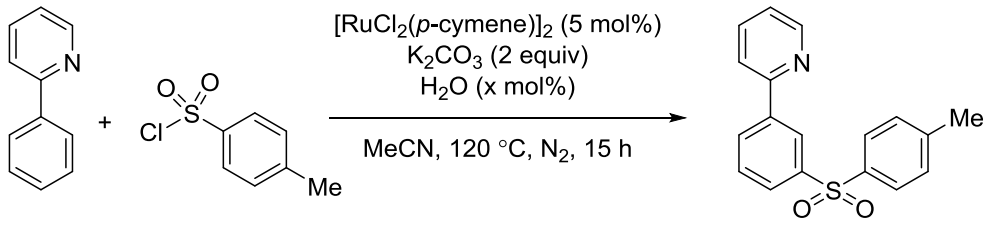
entry[a]	temp (°C)	Time (h)	yield (%)[b]
1	120	20	32
2	120	15	32
3	90	15	0

[a]Reaction conditions: 2-phenylpyridine (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), MeCN (3 mL), N_2, temperature and time. [b]Isolated yield.

Next, the effect of water on the reaction was investigated. The findings did not have a clear correlation between the addition of water and the yield of the *meta*-sulfonated product formed. From the results shown in Table 3, when the reaction was carried out in air, the yield dramatically

dropped to 2% (Table 3, entry 5). In contrast with 0.5 mol% of water, this had no effect on the yield (Table 3, entry 3). However, when 5 mol% of water is used, the yield was reduced to 19% (Table 3, entry 4). Contrastingly, the reaction in deuterated acetonitrile (CD_3CN) which contains 0.05 mol% of water, gave the *meta*-sulfonated product in 57% yield. The results indicate there is a possibility that a catalytic amount of water might enhance the reaction, possibly to generate a catalytic amount of *p*-tosic acid (*p*-TsOH).

Table 3. Optimisation for the effects of water/moisture on the *meta*-sulfonation



63 **316a** (3 equiv) **318a**

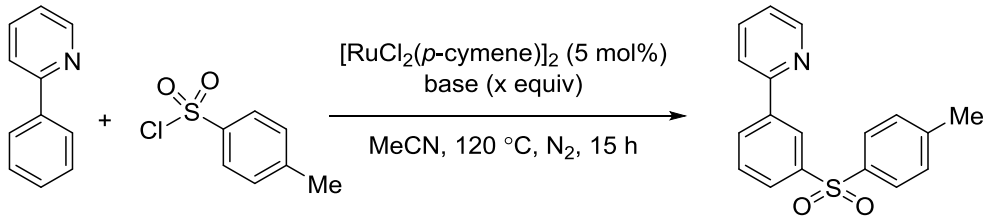
entry[a]	H_2O (mol%)	yield (%)[b]
1	0.01	trace
2	0.5	30
3	0.8	57[c]
4	5	19
5	air	2
6	Ar	30

[a]Reaction conditions: 2-phenylpyridine (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), H_2O (x mol%), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yield. [c]CD_3CN (3 mL, contains 0.05% H_2O, but calculated as 0.8 mol% water content relative to 2-phenylpyridine)

The base used in the sulfonation reaction was also examined and the stoichiometry of K_2CO_3 was varied to investigate the effects of the base on the reaction. Interestingly, by increasing the equivalence of K_2CO_3 to 2.5 afforded the product in 54% yield (Table 4, entry 2) which seems to be the threshold point. Because when more than 2.5 equivalents of K_2CO_3 is added to the reaction (Table 4, entry 3 and 4), the yield decreased and it seems to have a detrimental effect on the reaction. The base was ground to give finer particles that would provide more surface area to react in the reaction and ground K_2CO_3 provided the *meta*-product in 45% yield (Table 4, entry 6). NaOAc and KOAc were also examined as bases in the reaction, as these bases have been reported

in the literature for synthesising C-H activated complexes.[42-44] The results indicated that K_2CO_3 is superior as a base compared to NaOAc and KOAc (Table 4, entries 5 and 7).

Table 4. Optimisation for the effects of base on the *meta*-sulfonation



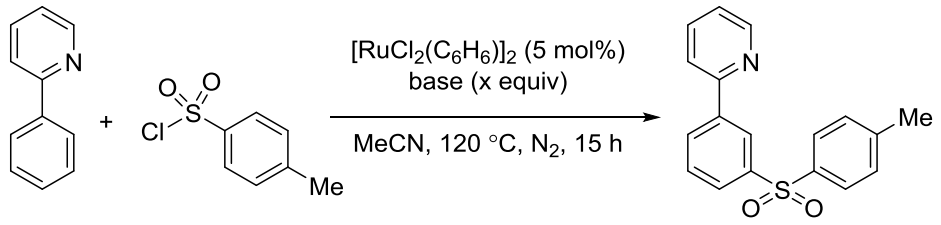
63 **316a** (3 equiv) **318a**

entry[a]	base	equivalence	yield (%)[b]
1	K_2CO_3	2	32
2	K_2CO_3	2.5	54
3	K_2CO_3	3	41
4	K_2CO_3	5	trace
5	NaOAc	2.5	31
6	ground K_2CO_3	2	45
7	ground KOAc	2	41

[a]Reaction conditions: 2-phenylpyrdine (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), base (x equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yield.

To ensure that $[RuCl_2(p\text{-cymene})]_2$ is the best catalyst for the present sulfonation, $[RuCl_2(C_6H_6)]_2$ was also examined because of its similarities in structure as $[RuCl_2(p\text{-cymene})]_2$, as the only difference is the η^6-ligand. This will provide some insight to the catalytic species involved in the catalytic cycle. In the presence of 5 mol% $[RuCl_2(C_6H_6)]_2$ and 2 equivalents of K_2CO_3 provided the *meta*-sulfonated product in 39% yield (Table 5, entry 1), which is a slightly improved yield compared to the standard conditions. Similar to the reaction using $[RuCl_2(p\text{-cymene})]_2$, employing more than 2 equivalents of K_2CO_3 did not aid the reaction (Table 5, entry 2). Although $[RuCl_2(C_6H_6)]_2$ is slightly more efficient than $[RuCl_2(p\text{-cymene})]_2$, however, $[RuCl_2(C_6H_6)]_2$ is much more expensive (£101.50 per gram) compared to $[RuCl_2(p\text{-cymene})]_2$ (£45.80 per gram), due to the cost, $[RuCl_2(p\text{-cymene})]_2$ was chosen as the preferred catalyst.

Table 5. Optimisation for the use of $[RuCl_2(C_6H_6)]_2$ as the catalyst with different bases in the *meta*-sulfonation



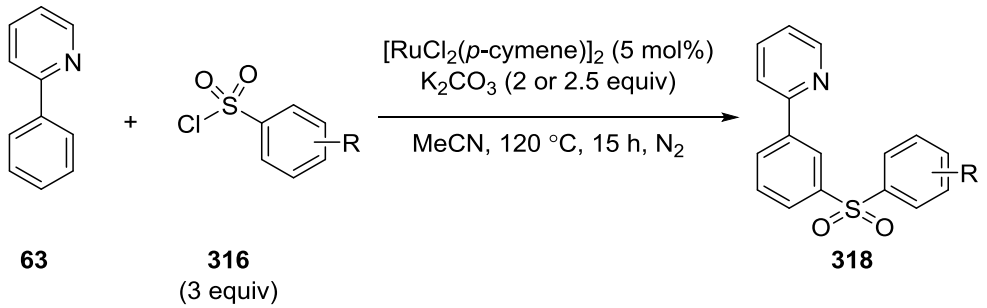
63 **316a** (3 equiv) **318a**

entry[a]	base	equivalence	yield (%)[b]
1	K_2CO_3	2	39
2	K_2CO_3	2.5	15
3	NaOAc	2.5	20

[a]Reaction conditions: 2-phenylpyrdine (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), base (x equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yield.

The optimised reaction conditions were utilised with other aryl sulfonyl chloride derivatives **316**, where the number of equivalence of K_2CO_3 is the independent variable to ensure that the optimised conditions can be generalised to other sulfonyl chlorides **316**. From Table 6, it is clearly highlighted that using more than 2 equivalents of K_2CO_3 does not aid the productivity. The use of 2.5 equivalents of K_2CO_3 made little difference to the reaction between 2-phenylpyridine and 4-bromobenzenesulfonyl chloride **316b** (Table 6, entry 4). In contrast to the reaction of 2-phenylpyridine with 4-fluorobenzenesulfonyl chloride **316c**, the yield dropped from 62% to 44% yield (Table 6, entries 5 and 6). It seems that the optimised conditions are only an isolated case for the reaction of 2-phenylpyridine **63** with *p*-TsCl **316a**.

Table 6. Comparison study on the effects of the equivalence of K_2CO_3 employed in the *meta*-sulfonation



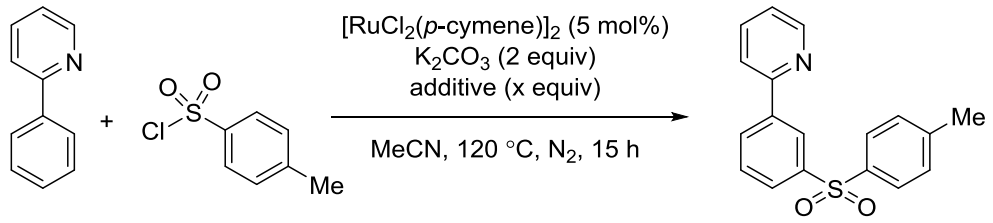
63 **316** (3 equiv) **318**

entry[a]	Ar	product	yield (%)[b]
1	4-MeC_6H_4 (**316a**)	**318a**	32
2	4-MeC_6H_4 (**316a**)	**318a**	54[c]
3	4-BrC_6H_4 (**316b**)	**318b**	23
4	4-BrC_6H_4 (**326b**)	**318b**	24[c]
5	4-FC_6H_4 (**316c**)	**318c**	62
6	4-FC_6H_4 (**316c**)	**318c**	44[c]

[a]Reaction conditions: 2-phenylpyrdine (1.0 mmol), sulfonyl chloride **316** (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yield. [c]K_2CO_3 (2.5 equiv).

Nucleophilic catalysts were examined as additives in the *meta*-sulfonation reaction (Table 7). Addition of 10 mol% of *N*-methyl imidazole made no impact to the reaction (Table 7, entry 1), but when 10 mol% of 4-dimethylaminopyridine (DMAP) was employed; the *meta*-sulfonated product was provided in 52% isolated yield (Table 7, entry 2). A controlled experiment was carried out in the absence of K_2CO_3, utilising DMAP as the sole base gave no products at all (Table 7, entry 4). This result suggests that the mechanism is most likely *via* carbonate-assisted C-H metallation, which is in agreement with the work of Dixneuf and Ackermann. [45-47]

Table 7. Optimisation study on the effects of organic bases as additives in the *meta*-sulfonation

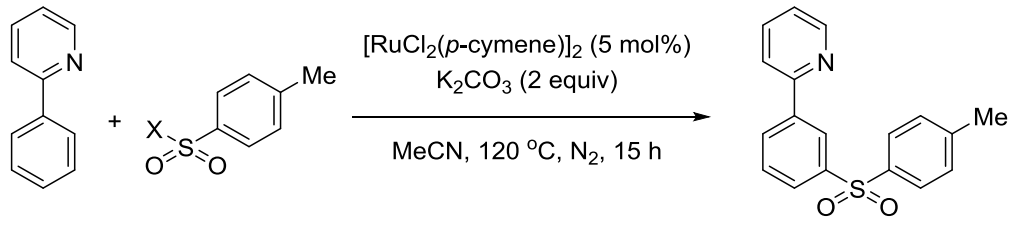


entry[a]	additive	equivalence	yield (%)[b]
1	*N*-methyl imidazole	0.1	37
2	DMAP	0.1	52
3	DMAP	0.2	27[c]
4	DMAP	1	0[d]

[a]Reaction conditions: 2-phenylpyridine (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), additive (x equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields. [c] K_2CO_3 (2.5 equiv). [d]In the absence of K_2CO_3.

On the basis that a small amount of DMAP facilitated the *meta*-sulfonation, it was of interest to investigate various sulfonating reagents. A variety of sulfonating reagents were synthesised and subjected to the standard conditions (Table 8). Unfortunately, all of the sulfonating reagents other than *p*-TsCl were unreactive under the *meta*-sulfonation conditions.

Table 8. Optimisation study the effects of various sulfonating reagents on the *meta*-sulfonation



63 **318a**

entry[a]	X	yield (%)[b]
1	Cl	32
2	Cl	0[c]
3	OH	0[d]
4	imidazole (**320**)	0
5	Benzotriazole (**321**)	0
6	DBN*	0

[a]Reaction conditions: 2-phenylpyridine (1.0 mmol), sulfonating reagent (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields. [c]*p*-TsCl (1.0 equiv). [d]*p*-TsOH.H_2O. * Provided by Dr Steve Bull's group.

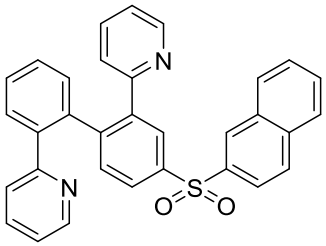
The order that the reagents were added into the reaction tube was varied to see if it made any difference to the product yield. Firstly, 5 mol% of $[RuCl_2(p\text{-cymene})]_2$ was added followed by dry MeCN (3 mL) and stirred under N_2, then 2-phenylpyridine **63** was added and 2 equivalents of K_2CO_3 and left the mixture to stir under N_2. This was expected to form some of the C-H activated Ru-phenylpyridine substrate-complex *in situ*, as the C-H activated complex can by synthesised at room temperature in the presence of the metal catalyst, base and substrate.[42, 43, 48, 49] After 10 minutes *p*-TsCl **316a** was added and the reaction tube was purged with N_2 for 5 minutes with stirring. The reaction tube was then sealed under an atmosphere of N_2 and heated at 120 °C with stirring for 15 hours. By changing the order of addition of the chemicals has in fact facilitated the reaction and the desired product was obtained in 49% yield.

As mentioned before the reaction temperature is at 120 °C and the boiling point of MeCN is only 82 °C, therefore it would be better to use a solvent that is suitable for such a high reaction temperature. Butyronitrile (PrCN) was used as the reaction medium, as its boiling point is 117 °C and the temperature inside the reaction tube should almost reach 120 °C. Reaction in

butyronitrile gave the desired product in 49% yield. Reaction in PrCN was performed with the same efficiency as in MeCN, however, unidentifiable side-products were observed by TLC analysis as well as in the crude ^{1}H NMR spectrum for the reaction in PrCN, making it more difficult to purify the products. Taking this into account, MeCN was opted as the reaction solvent for the *meta*-sulfonation.

The only alteration made to the standard conditions was the order of adding the chemicals; otherwise, everything else was kept the same as before. With the conditions in hand, the scope of the ruthenium-catalysed *meta*-sulfonation was explored. Various aryl sulfonyl chlorides were reacted with 2-phenylpyridine and produced the *meta*-sulfonated products in moderate to good yields (Table 9). Interestingly, electron deficient sulfonyl chlorides containing substituents such as NO_2 and CN performed poorly in the reaction and obtained the corresponding products in low yields (Table 9, entries 11 and 12). This observation is unusual, because if the reaction is *via* the S_EAr mechanism then a more electron deficient electrophile should be more reactive in the substitution reaction. In contrast, sulfonyl chlorides containing electron-rich substituents were more efficient as coupling partners, for example, 4-methoxybenzenesulfonyl chloride provided the corresponding product **318h** in 60% yield (Table 9, entry 6). But it is noteworthy that Dong has also observed similar results in the *ortho*-sulfonation study of 2-phenylpyridine.[33] The use of mesityl and 2,4,6-triisopropylbenzene sulfonyl chloride afforded the products **318i** and **318j** in poor yields of 5 and 11% respectively (Table 9, entries 7 and 8). This may be attributed to the increased steric demands of the two *ortho* substitutents. Useful functional handles such as bromide and fluoride that are prone to react with transition metals were tolerated in the reaction and obtained in good yields.

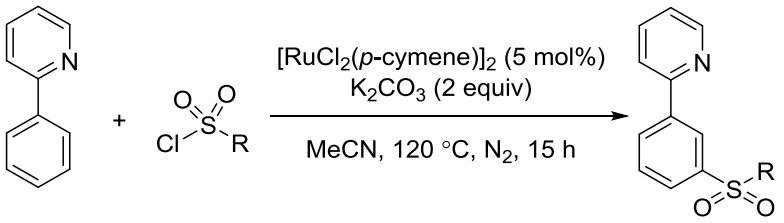
Interestingly, reaction between 2-phenylpyridine and naphthylsulfonyl chloride formed the desired product **318k** in 63% yield (Table 9, entry 9), as well as a trace amount of a by-product that was identified by MS, with a molecular ion mass of 499.1474 gmol^{-1}. A possible structure would be the heterodimer **322**, with a molecular formula of $C_{32}H_{22}N_2O_2S$ $[M+H]^+$ (Scheme 118).



322

Scheme 118

Table 9. Scope of ruthenium(II) catalysed *meta*-sulfonation



63 **316** (3 equiv) **318**

entry[a]	R	product	yield (%)[b]
1	4-MeC_6H_4 (**316a**)	**318a**	49
2	4-BrC_6H_4 (**316b**)	**318b**	23
3	4-FC_6H_4 (**316c**)	**318c**	62
4	C_6H_5 (**316d**)	**318d**	48
5	2-MeC_6H_4 (**316e**)	**318e**	28
6	3-MeC_6H_4 (**316f**)	**318f**	50
7	4-^{t}BuC_6H_4 (**316g**)	**318g**	54
6	4-$OMeC_6H_4$ (**316h**)	**318h**	61
7	Mes (**316i**)	**318i**	5
8	2,4,6-^{i}Pr-C_6H_2 (**316j**)	**318j**	11
9	1-naphthalene (**316k**)	**318k**	63[c]
10	3-BrC_6H_4 (**316l**)	**318l**	31
11	4-$NO_2C_6H_4$ (**316m**)	**318m**	9
12	4-CNC_6H_4 (**316n**)	**318n**	4
13	2-BrC_6H_4 (**316o**)	**318o**	18
14	4-$SO_2MeC_6H_4$ (**316p**)	-	0
15	8-quinoline (**316q**)	-	0

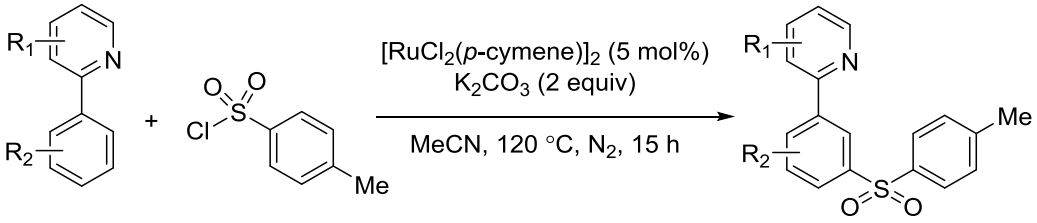
16	Me (**316r**)	-	0
17	^{n}Bu (**316s**)	-	0

[a]Reaction conditions: 2-phenylpyridine (1.0 mmol), sulfonyl chloride **316** (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields.

Contrary to arylsulfonyl chlorides, aliphatic sulfonyl chlorides were not compatible in the reaction, this could be due to the protons that are positioned α to the sulfone (Table 9, entries 14, 16, 17), which makes the α-protons more acidic, and considering the high reaction temperature, the α-protons have a high chance of undergoing deprotonation. In addition, 8-quinoline sulfonyl chloride did not react with 2-phenylpyridine, but this might be due to the nitrogen on the quinoline ring competing with the pyridine nitrogen for coordination to the ruthenium centre.

Dr Ourida Saidi performed *meta*-sulfonation with other 2-phenylpyridine derivatives **316** and *p*-TsCl **309a** under the standard conditions. Interestingly, a *meta*-substituent on the substrate **323e** leads to no product formation (Table 10, entry 6). This suggests cyclometallation proceeds *via* the least hindered C-H bond resulting in a complex where the methyl group is *para* to the activating Ru-C_{aryl} σ-bond. Therefore, the *meta* methyl group has blocked the reaction site, hence no reaction can take place. This finding provides further evidence that the present reaction could be *via* a chelation-assisted σ-activation pathway. In addition, reaction with phenyl isoquinoline **323c** and *p*-TsCl afforded the product in 40% isolated yield (Table 10, entry 4). The lower yield could be the result of steric interactions from the isoquinoline, hindering the C-H metallation step.

Table 10. Substrate scope of *meta*-sulfonation carried out by Dr Ourida Saidi

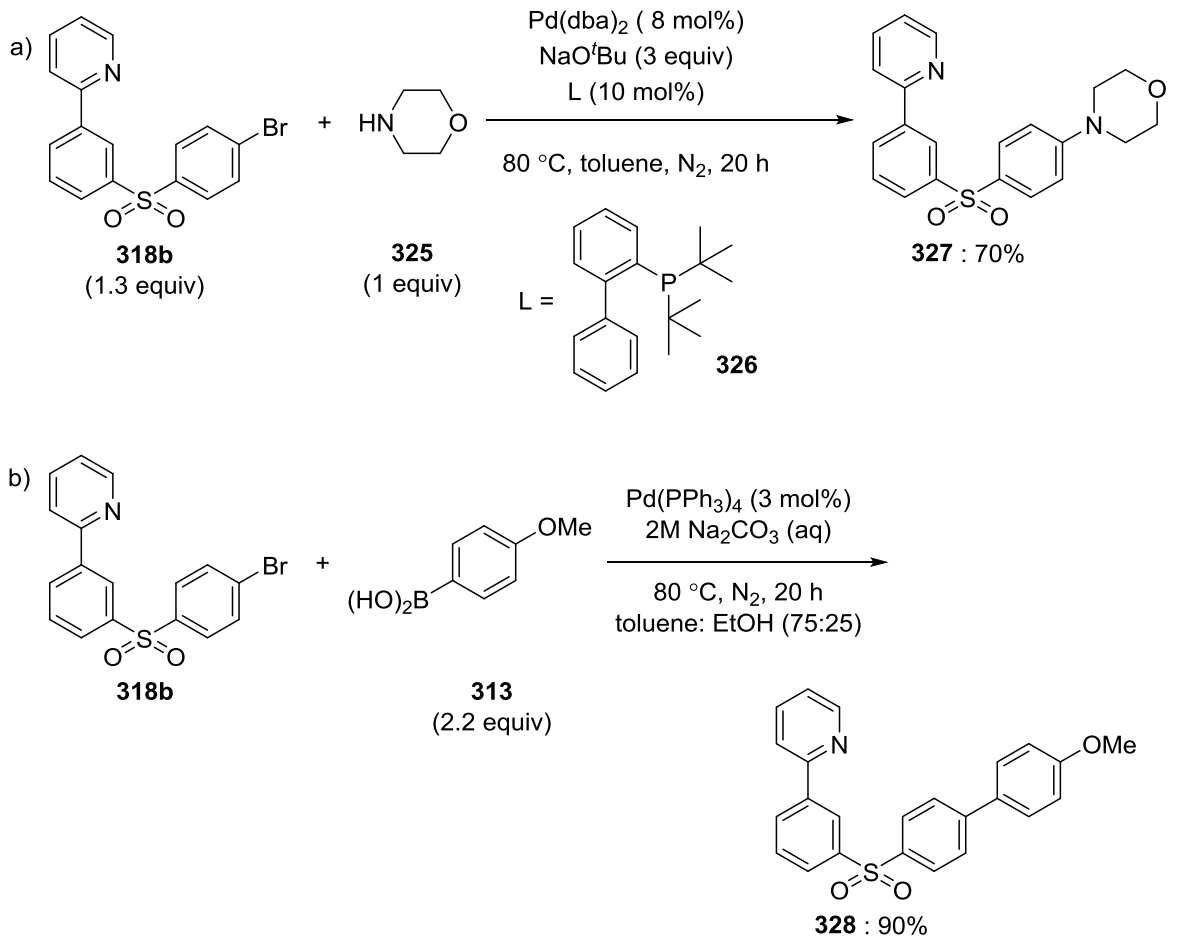


323 **316a** (3 equiv) **324**

entry[a]	R_1	R_2	product	yield (%)[b]
1	H	4-Me (**208**)	**324a**	56 (41)[d]
2	H	4-OMe (**323a**)	**324b**	43
3	3-Me	H (**323b**)	**324c**	48
4	phenyl[c]	H (**323c**)	**324d**	40
5	phenyl[c]	4-Me (**323d**)	**324e**	33
6	H	3-Me (**323e**)	**324f**	0

[a]Reaction conditions: 2-phenylpyridine derivative(1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields. [c]directing group = 1-isoquinoline. [d]Replicated reaction.

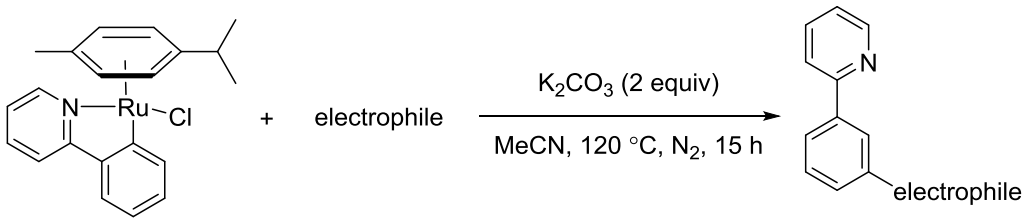
The bromo substituent in the product allows for further synthetic modification, this was demonstrated when compound **318b** was subjected to Pd(0)-catalysed Buchwald-Hartwig amination and Suzuki-Miyaura cross-coupling conditions and obtained the coupled products **327** and **328** in 70 and 90% isolated yield respectively (Scheme 119).



Scheme 119

The next step was to establish whether 2-phenylpyridine **63** will react with other electrophiles and undergo *meta* C-H functionalisation. Stoichiometric studies of complex **319** with various electrophiles under standard conditions are shown in Table 11. Unfortunately, the experiments showed no indication of products formed in the crude ^{1}H NMR spectrum.

Table 11. Stoichiometric reactions of complex 312 with various electrophiles

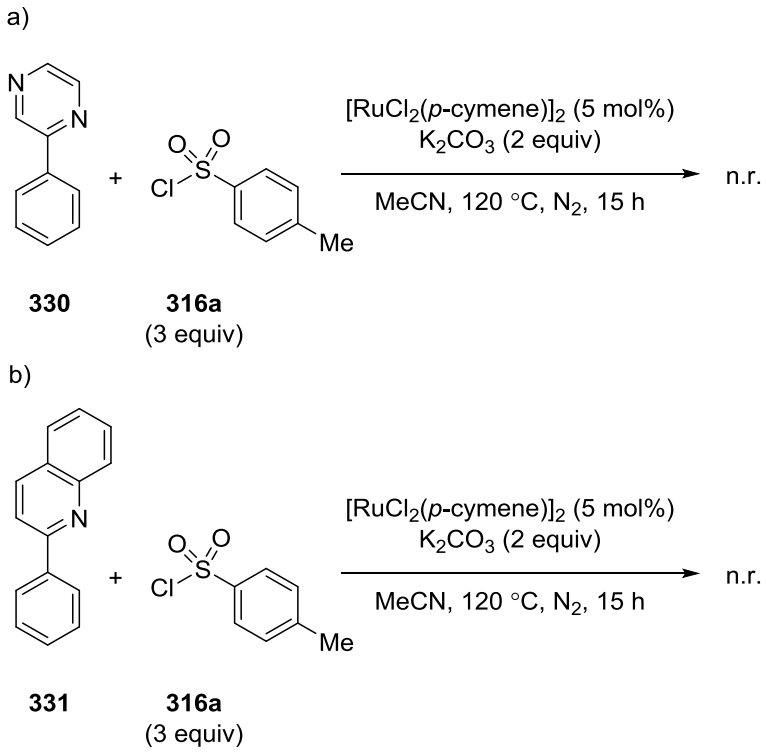


319 **329**

entry[a]	electrophile	yield (%)[b]
1	NBS	0
2	cyclopentenone	0
3	dimethylitaconate	0
4	*p*-toluene isocyanate	0
5	acetic anhydride	0

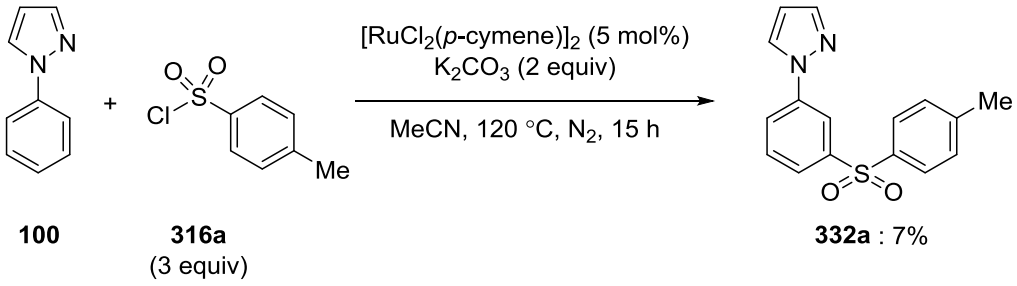
[a]Reaction conditions: **319** (0.09 mmol), electrophile (0.09 mmol), K_2CO_3 (2 equiv), MeCN (2 mL), 120 °C, N_2, 15 h. [b]Isolated yield.

Having failed to identify a new electrophile, the next step was to extend the *meta*-sulfonation reaction with other chelating groups or substrates. Various directing groups were reacted under the *meta*-sulfonation conditions. Pyrazine **330** and quinoline **331** did not react with *p*-TsCl **316a** and only the starting materials were observed (Scheme 120). It was unsure why both of these directing groups failed to react as both pyrazine and quinoline have shown to be compatible chelating groups in ortho C-H functionalisation reactions.[50-55]



Scheme 120

1-Phenylpyrazole **100** was compatible with the *meta*-sulfonation conditions and provided the *meta*-sulfonated product albeit in a low yield of 7% (Scheme 122).



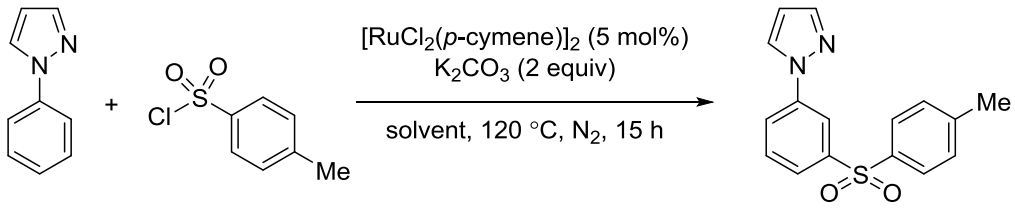
Scheme 121

2.4.2b. *Meta*-sulfonation of 1-phenylpyrazole

Because pyrazole is an important structural motif in biologically active molecules, it would be of interest to optimise the *meta*-sulfonation of 1-phenylpyrazole.[56, 57] Pyrazole possess two nitrogen atoms in a 5-membered aromatic ring, and they are structurally and chemically different from the

pyridine ring. As such, it was logical to perform a solvent screen for the *meta*-sulfonation of 1-phenylpyrazole as shown in Table 12.

Table 12. Solvent screen of 1-phenylpyrazole and *p*-TsCl *meta*-sulfonation



100 **316a** (3 equiv) **332a**

entry[a]	solvent	yield (%)[b]
1	MeCN	7 (3)[c]
2	propionitrile	12
3	butyronitrile	9
4	chlorobenzene	14
5	ethyl acetate	Trace
6	toluene	5
7	acetone	1
8	DMF	0[d]
9	NMP	0
10	1,4-dioxane	4

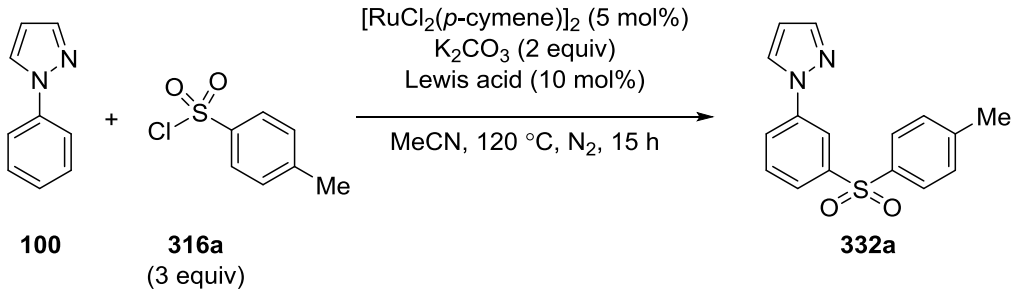
[a]Reaction conditions: 1-phenylpyrazole (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), solvent (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields. [c]24 h. [d]Mixture of by-products formed.

Only aprotic solvents were examined, because the presence of an acidic proton can interact with *p*-TsCl **316a** to form the acid. Polar aprotic solvents such as propionitrile and butyronitrile were compatible reaction media, but the yields are very similar to the ones produced under the standard conditions (Table 12, entries 2 and 3), it is noteworthy that by-products were observed in both cases. Dimethylformamide (DMF) and *N*-methylpyrrolidine (NMP) were not suitable solvents and in DMF, a mixture of unidentified by-products were found, but this could be due to DMF reacting under the standard conditions. In nonpolar aprotic solvents such as toluene gave 5% yield, whereas the reaction in chlorobenzene proceeded in 14% yield. Although chlorobenzene

was found to be the best solvent, it is not a green solvent and it is harmful to the environment; so the preferred solvent of choice is acetonitrile.

As mentioned previously, 1-tosyl-1*H*-imidazole and other sulfonating reagents were not reactive under the *meta*-sulfonation conditions. So another way to make the electrophile more reactive is by adding a Lewis acid to the reaction, in which the Lewis acid would withdraw electron density from the S=O bond, making it more electrophilic and prone to nucleophilic attack. Various Lewis acids were screened (Table 13) and unfortunately the results were disappointing. Only $InCl_3$ and $In(OTf)_3$ were compatible with the reaction, but the yields of the *meta*-sulfonated products were not improved (Table 13, entries 1 and 2).

Table 13. Lewis acid screen for *meta*-sulfonation of 1-phenylpyrazole with *p*-TsCl



100 **316a** (3 equiv) **332a**

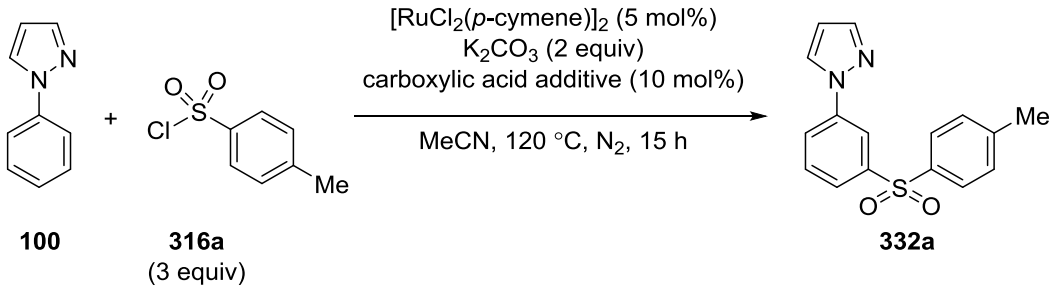
entry[a]	Lewis acid	yield (%)[b]
1	$InCl_3$	1
2	$In(OTf)_3$	7
3	$CuCl_2$	0
4	$Ti(O^iPr)_4$	0

[a]Reaction conditions: 1-phenylpyrazole (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), Lewis acid (10 mol%), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields.

The C-H activation mechanism for the *meta*-C-H sulfonation is most likely to be *via* the CMD mechanism as mentioned previously. A way to facilitate the C-H activation step is by the addition of acidic additives. *p*-Toluenesulfonic acid monohydrate, pivalic acid and methanesulfonic acid were subjected to the standard conditions independently, however no major improvements were made (Table 14). Pivalic acid was the most effective additive, and improved the yield to 12%,

which is not much difference compared to the yield obtained under the standard conditions (Table 14, entry 2).

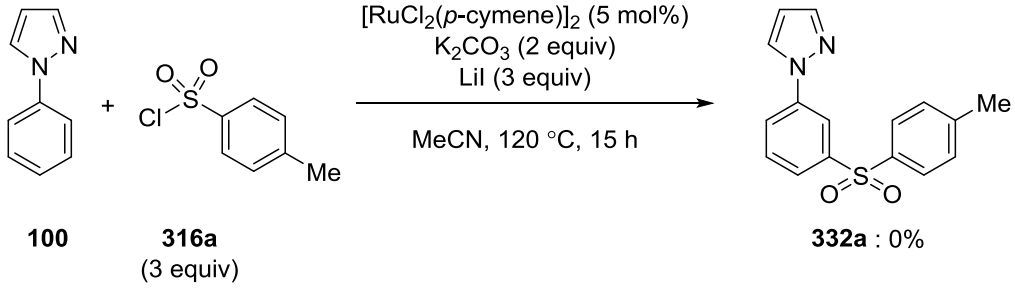
Table 14. Carboxylic acid screen for *meta*-sulfonation of 1-phenylpyrazole with *p*-TsCl



entry[a]	carboxylic acid	yield (%)[b]
1	*p*-TsOH.H_2O	7
2	pivalic acid	12
3	methanesulfonic acid	0

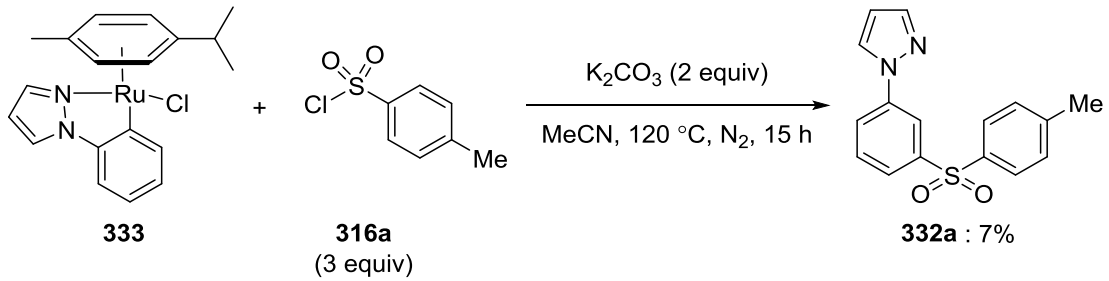
[a]Reaction conditions: 1-phenylpyrazole (1.0 mmol), *p*-TsCl (3.0 mmol), [$RuCl_2$(*p*-cymene)]$_2$ (5 mol%), K_2CO_3 (2 equiv), carboxylic acid (10 mol%), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields.

An *in situ* Finkelstein reaction was employed to exchange the halogen, by using lithium iodide, the chloride on *p*-TsCl should exchange with the iodide to give *p*-TsI, making it more reactive because iodide is a better leaving group and can be readily displaced in substitution reactions. Addition of 3 equivalents of lithium iodide under the standard conditions gave no products and only the starting materials were recovered (Scheme 122).



Scheme 122

The poor outcome for the *meta*-sulfonation of 1-phenylpyrazole is unusual, as 1-phenylpyrazole has been used as a substrate for many C-H functionalisation reactions.[58-63] So the ruthenium substrate complex was synthesised as in the literature as reported by Dixneuf *et al.* and obtained complex **333** in 82% yield.[43] A stoichiometric reaction between the complex and *p*-TsCl afforded the desired product in 7% isolated yield (Scheme 123). This result was unexpected, since the substrate is already in its C-H activated form, so it should react with 100% conversion. This finding indicates that the problem is the substrate itself. The nitrogen on the pyrazole might be strongly coordinated to the Ru centre, so unable to release electron density to the arene to perform the S_EAr reaction.

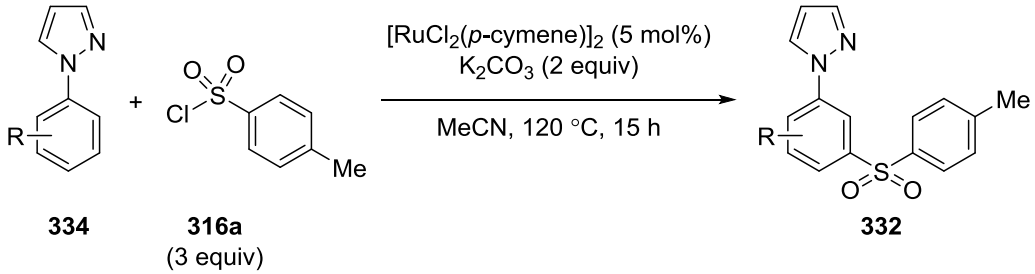


333 **316a** (3 equiv) **332a** : 7%

Scheme 123

To ensure that the reactivity observed in 2-phenylpyridine derivatives can be related to other phenylpyrazole derivatives, 1-(*p*-tolyl)-1*H*-pyrazole **334a** and 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** were synthesised and subjected under the standard *meta*-sulfonation conditions (Table 15). As expected the **334a** was reactive and gave the *meta*-sulfonated product in 10% yield, in contrast **334b** was unreactive. This finding agrees with the result obtained for 3-tolylpyridine **323e** and supports the proposed mechanism proceeds *via* an σ-activation pathway.

Table 15. Substrate scope of *meta*-sulfonation

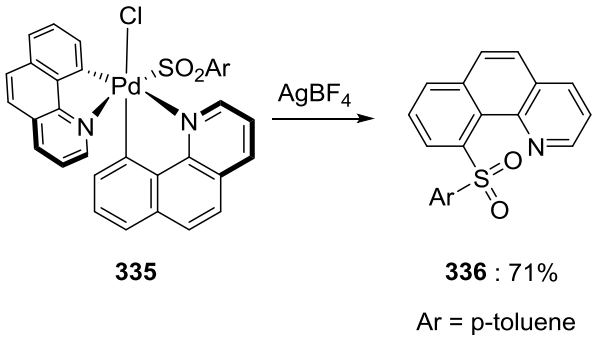


entry[a]	R	product	yield (%)[b]
1	H (**100**)	**332a**	7
2	4-Me (**334a**)	**332b**	10
3	3-OMe (**334b**)	**-**	-

[a]Reaction conditions: 1-phenylpyrazole derivative (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields.

2.4.2c. *Meta*-sulfonation of benzo[*h*]quinoline

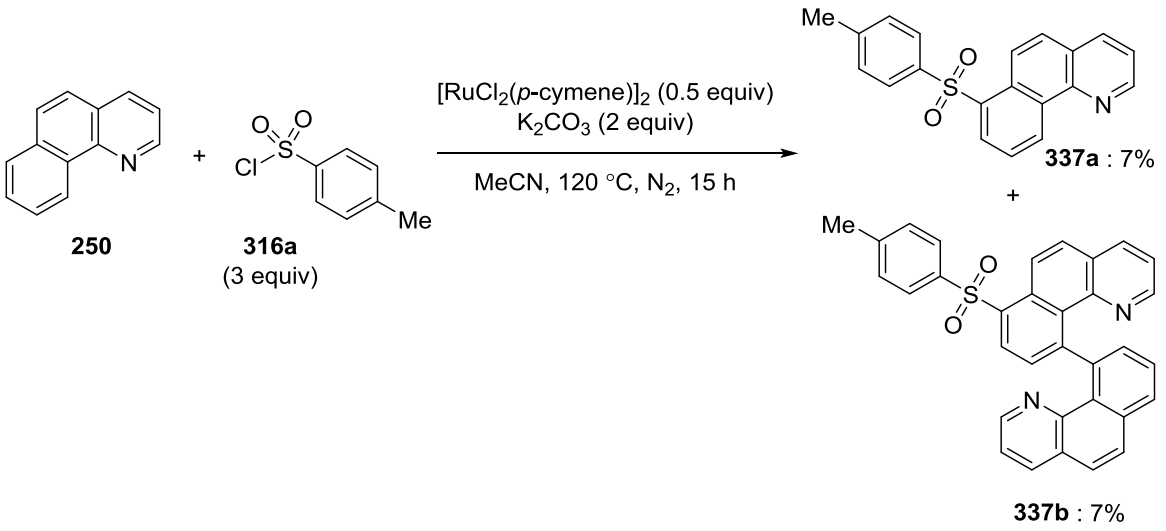
In the study by Dong on the *ortho* C-H sulfonation reaction, they also studied benzo[*h*]quinoline, but it gave the desulfinated product **317**.[33] They were only able to obtain the pseudo-*ortho* sulfonated benzo[*h*]quinoline **336** from the Pd-benzo[*h*]quinoline complex **335** (Scheme 124).[64]



Scheme 124

Therefore, it would be interesting to see if benzo[*h*]quinoline would be compatible with our *meta*-sulfonation conditions. Treatment of benzo[*h*]quinoline with *p*-TsCl, in the presence of 5 mol% $[RuCl_2(p\text{-cymene})]_2$ and 2 equivalents of K_2CO_3 in MeCN at 120 °C, after 15 hours, TLC analysis showed several new faint spots. However, after purification by column chromatography, a

mixture of products were isolated, the structures of which was difficult to elucidate from spectroscopic analysis. Therefore, the reaction was repeated on a larger scale, after purification a new compound was isolated as a mixture of two products. Further purification was able to separate the mixture of products. Spectroscopic analysis *via* 1D and 2D ^{1}H and ^{13}C NMR spectroscopy revealed one product was a pseudo-*meta*-sulfonated product **337a** in 7% yield and another product isolated in 7% yield, which was a pseudo-*meta*-sulfonated heterodimer **337b** (Scheme 125). The structure of the *meta*-sulfonated heterodimer **337b** was confirmed by X-ray crystallography (Figure 1).



Scheme 125

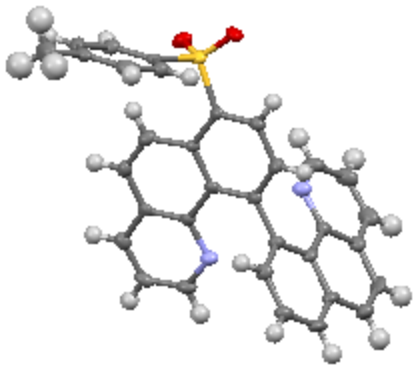


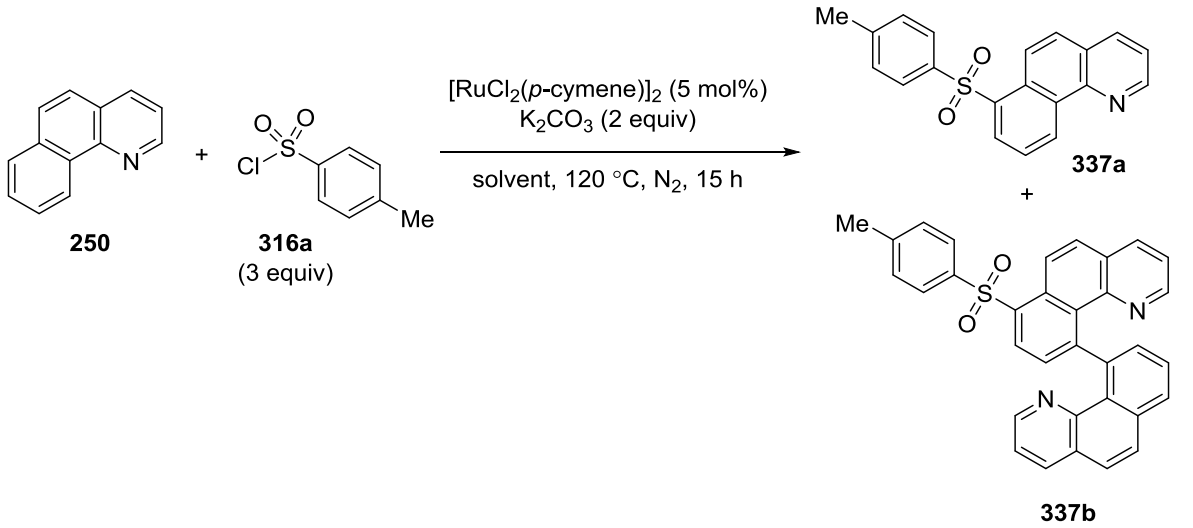
Figure 1. X-ray crystal structure of 337b

The structure of the heterodimer **337b** is interesting, from Figure 1, it shows that the two benzo[*h*]quinolines are not in the same plane, one benzo[*h*]quinoline is in plane and the other

benzo[*h*]quinoline molecule is out of the plane, therefore the two nitrogen atoms are facing in opposite directions. In addition, the arylsulfone moiety is not in the same plane as the two benzo[*h*]quinoline, which gives this structure a twisted shape. The structure of **337b** seems to be similar to the structure of chiral ligands such as BINAP, which contains a chiral axis due to restricted rotation on the bond linking the two naphthyl rings. With **337b**, the bond linking the two benzo[*h*]quinoline seems to be restricted in rotation around the bond because of steric hinderance from the sulfone moeity. Because of the similarities in the structures between **337b** and BINAP, **337b** may have potential applications as a ligand in transition metal catalysis. Therefore, it would be useful to optimise this reaction and with enough of this heterodimer in hand to explore the heterodimer as a possible ligand with various transition metal catalysts.

Column chromatography afforded the two products as a mixture for the optimisation study of *meta*-sulfonation of benzo[*h*]quinoline. Firstly a solvent screen was performed, various solvents were examined including PrCN, 1,4-dioxane, THF and DMF (Table 16). Although reaction in PrCN provided the highest yield of 38% (Table 16, entry 2), however, the products isolated were not clean and the purification was hindered with the presence of other unknown by-products. Reaction in 1,4-dioxane, tetrahydrofuran (THF) and DMF did not improve the yields (Table 16, entries 3 – 5). The best option was to continue to use MeCN as the reaction solvent, as it was easier to use and gave the best yield after PrCN, without co-eluting side product formation.

Table 16. Solvent screen for *meta*-sulfonation of benzo[*h*]quinoline with *p*-TsCl

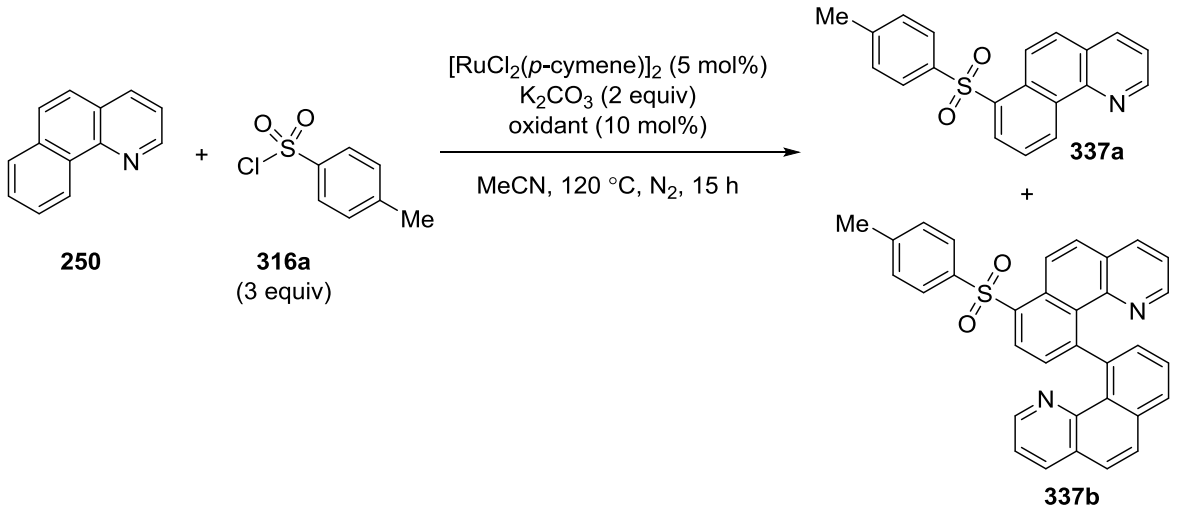


entry[a]	solvent	yield of **337a** & **337b** (%)
1	MeCN	14
2	PrCN	38
3	1,4-dioxane	12
4	THF	9
5	DMF	4

[a]Reaction conditions: benzo[*h*]quinoline (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), solvent (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields of product **337a** and **337b** as a mixture.

The next task was to examine various oxidants, to see if they would help to regenerate the catalyst in the catalytic cycle (Table 17). In the presence of 10 mol% of an oxidant in the sulfonation reaction, only $Cu(OAc)_2$ worked in the reaction, and afforded the product in 12% yield (Table 17, entry 1). While increasing the amount of $Cu(OAc)_2$ to 0.5 equivalent had a detrimental effect and gave the products in traces (Table 17, entry 2). In this regard, using an oxidant has little impact on the reaction.

Table 17. Oxidant screen for the *meta*-sulfonation of benzo[*h*]quinoline with *p*-TsCl



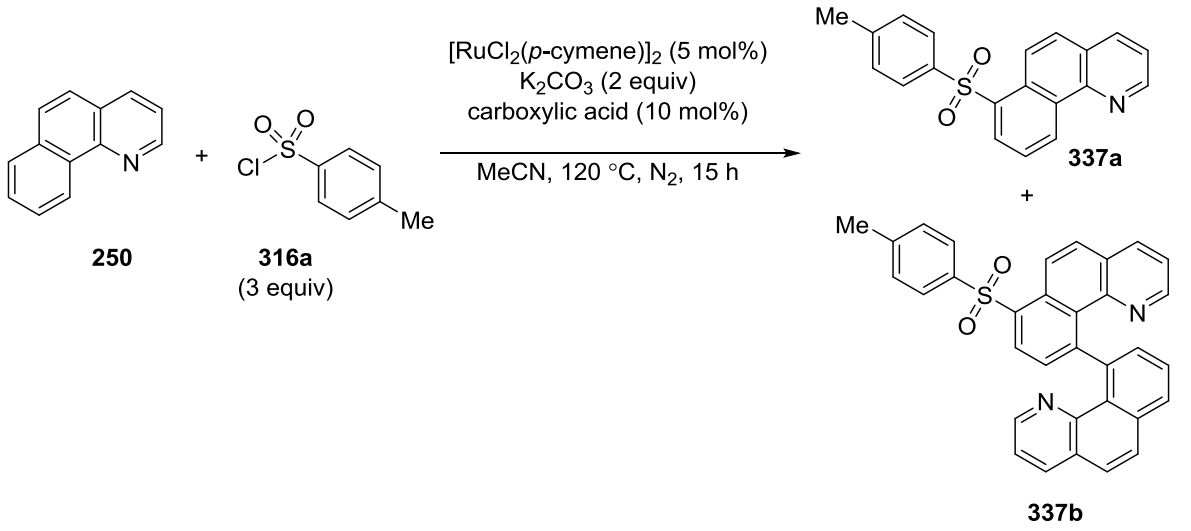
250 + **316a** (3 equiv) → **337a** + **337b**

entry[a]	oxidant	yield of **337a** & **337b** (%)[b]
1	$Cu(OAc)_2$	12
2	$Cu(OAc)_2$ (0.5 eq)	Trace
3	$Cu(OAc)_2.2H_2O$	Trace
4	$FeCl_3$	3
5	Ag_2O	7
6	$K_2S_2O_8$	0
7	O_2	0

[a]Reaction conditions: benzo[*h*]quinoline (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), oxidant (10 mol%), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields of product **337a** and **337b** as a mixture.

Various acids were examined to see if they would improve the reaction. Choosing a different carboxylate ligand might improve the CMD mechanism for forming the cyclometallacycle (Table 18). However, none of the carboxylic acids facilitated the reaction and poor yields were obtained.

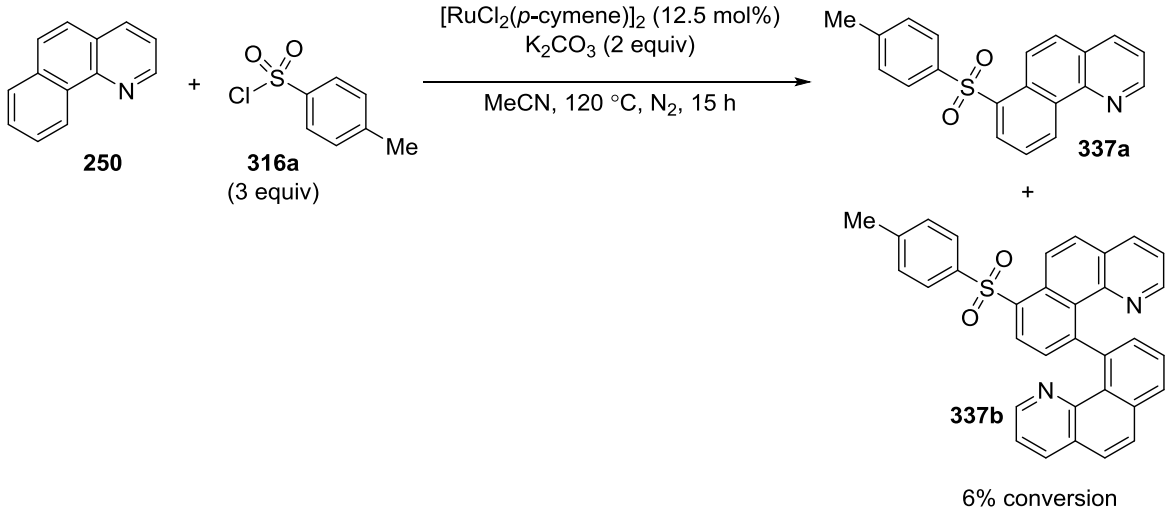
Table 18. Carboxylic acid screen for *meta*-sulfonation of benzo[*h*]quinoline with *p*-TsCl



entry[a]	carboxylic acid	yield of **337a** & **337b** (%)[b]
1	*p*-TsOH.H_2O	1
2	Pivalic acid	2
3	Benzoic acid	0
4	Mesitylene carboxylic acid	1

[a]Reaction conditions: benzo[*h*]quinoline (1.0 mmol), *p*-TsCl (3.0 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), carboxylic acid (10 mol%), MeCN (3 mL), 120 °C, N_2, 15 h. [b]Isolated yields of product **337a** and **337b** as a mixture.

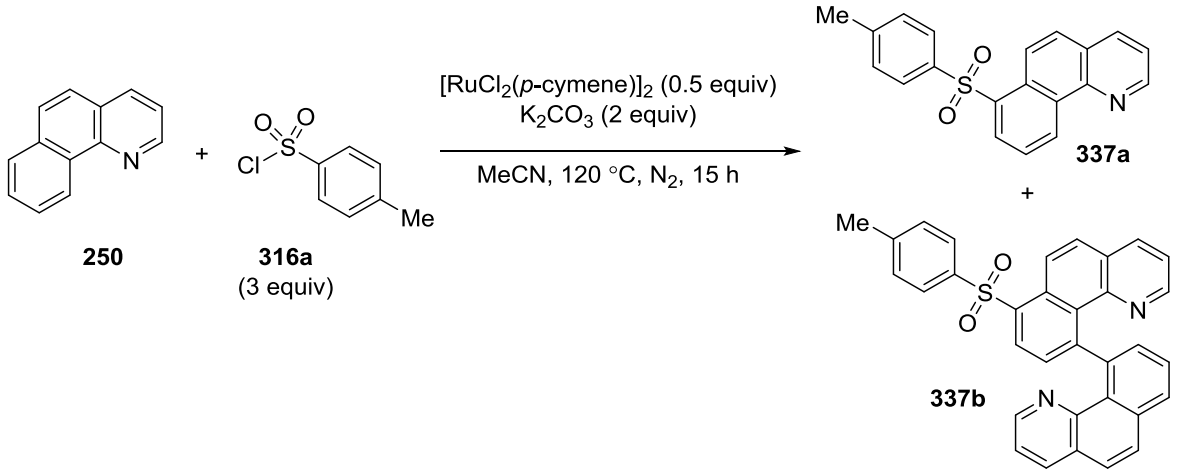
Increasing the catalyst loading to 12.5 mol%, did not aid the productivity, in fact the yield was halved, and gave only 6% conversion, meaning there was no catalytic turnover (Scheme 126).



Scheme 126

To obtain a better understanding of the reaction, stoichiometric experiments were performed using 0.5 equivalents of $[RuCl_2(p\text{-cymene})]_2$, and altering the stoichiometry of benzo[*h*]quinoline and *p*-TsCl in the presence of 2 equivalents of K_2CO_3 at 120 °C in MeCN (Table 19). From the results, it seems that using equimolar or less of *p*-TsCl compared to benzo[*h*]quinoline the reaction is unable to proceed and no products were observed. However, by increasing the amount of *p*-TsCl to 2.5 equivalents, some traces of product were isolated. This indicates that an excess of *p*-TsCl is needed for the reaction to take place, which can be an indication that during the reaction, *p*-TsCl could be participating in a side reaction. Hence, an excess of *p*-TsCl is necessary for the reaction to take place.

Table 19. Stoichiometric study of *meta*-sulfonation of benzo[*h*]quinoline with *p*-TsCl

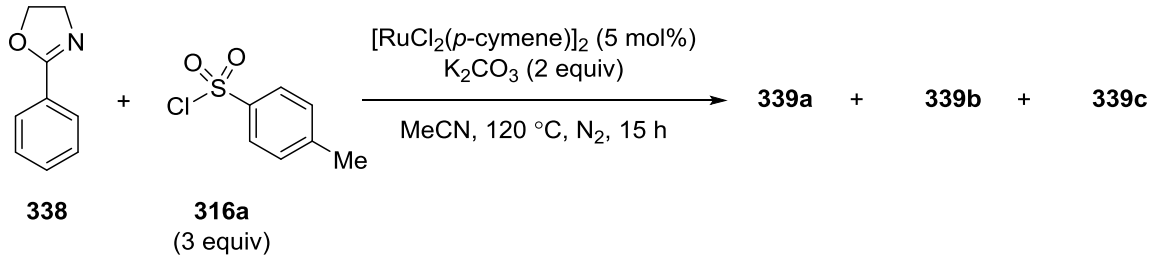


entry[a]	Benzo[*h*]quinoline (equiv)	*p*-TsCl (equiv)	yield of **337a** & **337b** (%)
1	1	0.5	-
2	1	1	-
3	2.5	1	-
4	1	2.5	traces

[a]Reaction conditions: benzo[*h*]quinoline (x mmol), *p*-TsCl (x mmol), $[RuCl_2(p\text{-cymene})]_2$ (0.08 mmol), K_2CO_3 (2 equiv), MeCN (1.5 mL), 120 °C, N_2, 15 h. [b]Isolated yields of product **337a** and **337b** as a mixture.

2.4.2d. *Meta*-sulfonation of 2-phenyl 2-oxazoline

Another directing group that was examined in the *meta*-C-H sulfonation reaction is 2-phenyl-2-oxazoline **338**, as this substrate has been shown to be a good substrate in many ruthenium catalysed C-H functionalisation reactions.[65-71] Treatment of 2-phenyl-2-oxazoline **338** with 3 equivalents of *p*-TsCl under the *meta*-sulfonation conditions afforded three different compounds (Scheme 127).



Scheme 127

The first thought was that one of the three compounds made could be the expected *meta*-C-H sulfonated product. Various 1D and 2D ^{1}H NMR and ^{13}C NMR experiments were implemented for the elucidation of the unknown compounds.

From the ^{1}H NMR of **339a** the integration adds up to the same number of protons as the "theoretical" C-H sulfonated product. However, the data from the mass spectra of **339a** disagrees with the molecular formula predicted for **339a**, which had a molecular ion of 360.0428 gmol^{-1}. So an X-ray crystallography analysis was conducted on **339a**. Unfortunately, it was not the C-H functionalised product as expected, instead a ring-opened product with a chlorine atom on the alkyl chain.

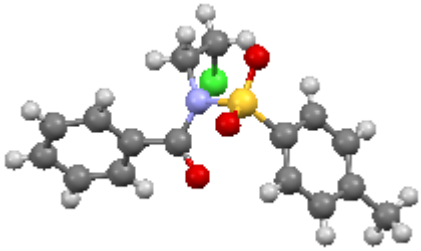


Figure 2. X-ray crystal structure 339a

In the ^{1}H NMR spectrum for **339b**, a distinct triplet is found at 5.80 ppm is clearly observed which is integrated as one proton. COSY 2D-NMR spectroscopy found that this particular triplet couples with two other CH_2 protons and the HSQC spectrum shows that this triplet is not directly attached to a carbon atom. Therefore, it was deduced that this proton must be attached to a heteroatom, which suggests an N-H or an O-H. From all of the information gathered deduced that **339b** is a ring-opened sulfonamide.

Whereas for **339c**, it can be clearly observed in the ^{1}H NMR spectrum that in the aliphatic region, the Me group peak is integrated to 6 protons, this suggests that there are two sets of Me groups present, meaning that there is the possibility of two tosyl groups coordinated to the nitrogen. This prediction was confirmed by X-ray crystallography and that **339c** does indeed have two *p*-tosyl groups attached to the nitrogen atom, giving a disulfonamide product.

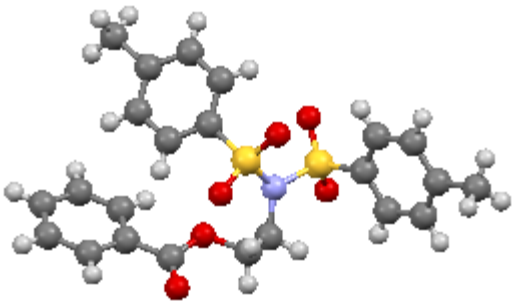
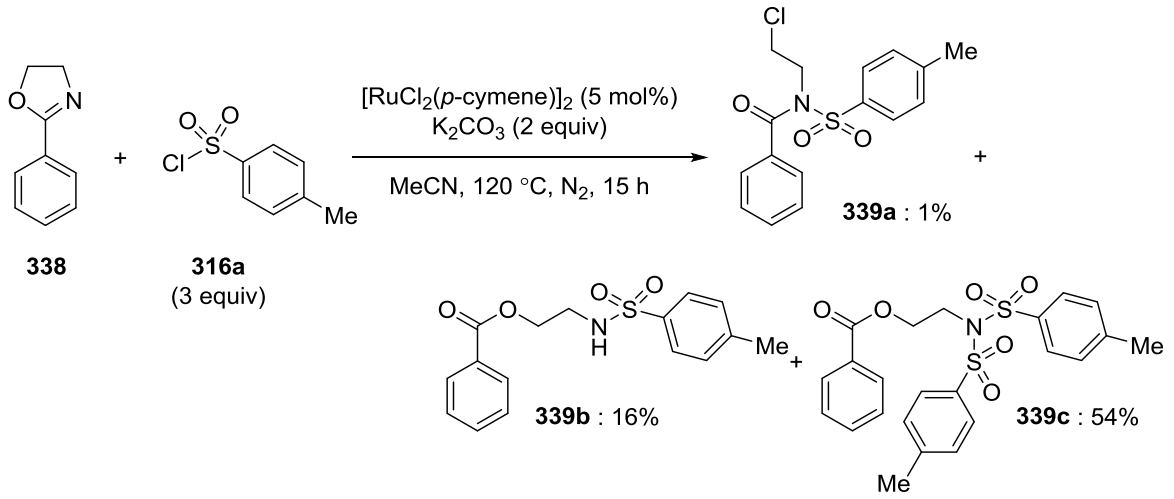
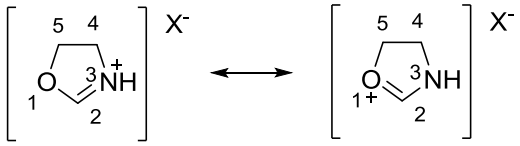


Figure 3. X-ray crystal structure of 339c



Scheme 128

The formation of **339a** can be explained. In the literature, Goldberg and Kelly suggested that the oxazoline can undergo ring-opening because of the resonance structures formed under certain conditions between an oxonium-ammonium ion (Scheme 129).[72]

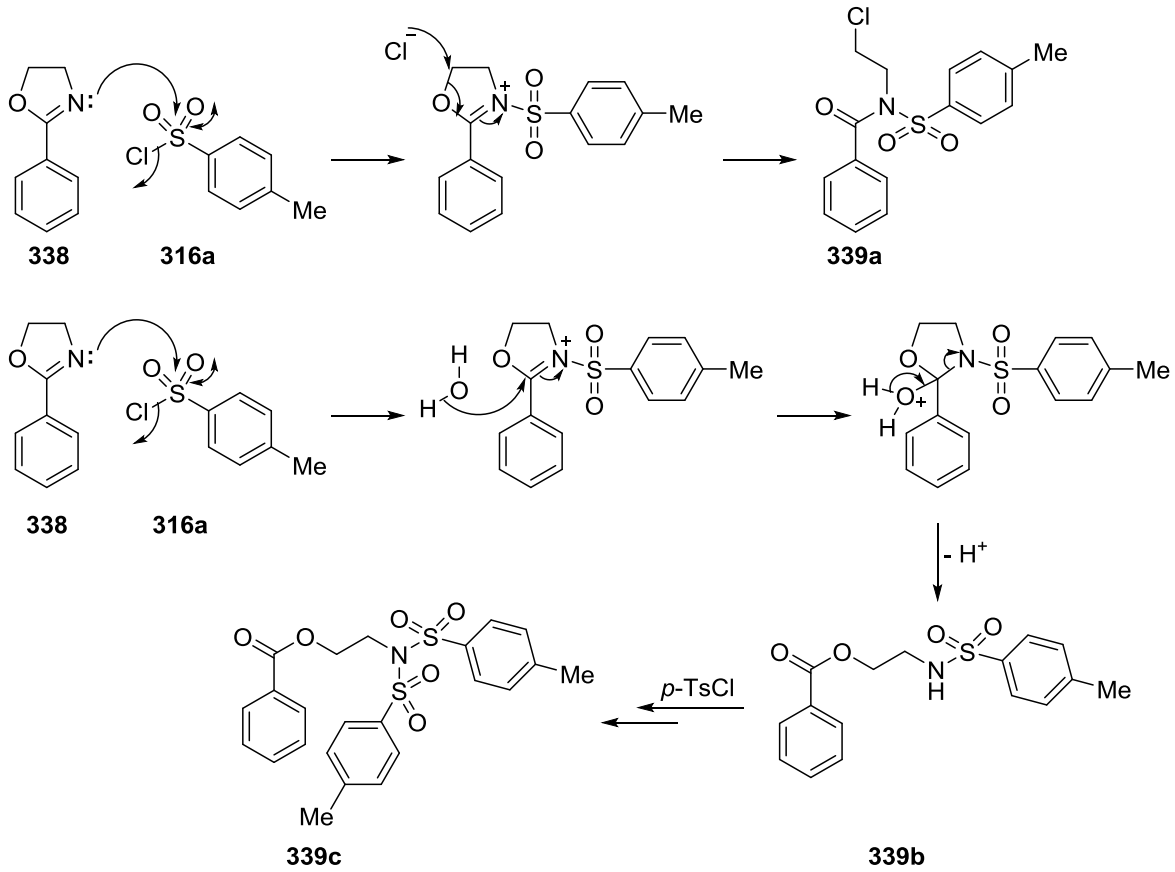


Scheme 129

As the resonance structures shows, the intermediates can behave as an imide as well as an oxonium ion. This resonance forms are vulnerable to nucleophilic attack at position 2 and 5. Fry stated that the salts formed are stable as long as there is no additional thermal energy that could facilitate the anion to add to position 5, which leads to ring cleavage. This is an irreversible process and the stable chloroethylamide is formed.[73]

For the formation of the chloro product **339a**, the likely mechanism is that the first step involves the nitrogen lone pair attacking the electrophile, *p*-TsCl, and the chloride is removed as a leaving group. The displaced chloride then acts as a nucleophile and attacks the oxazoline, which leads to ring-opening of oxazoline to afford the ring-opened chlorinated product **339a**.

A proposed mechanism for the formation of the three products is shown in Scheme 130.



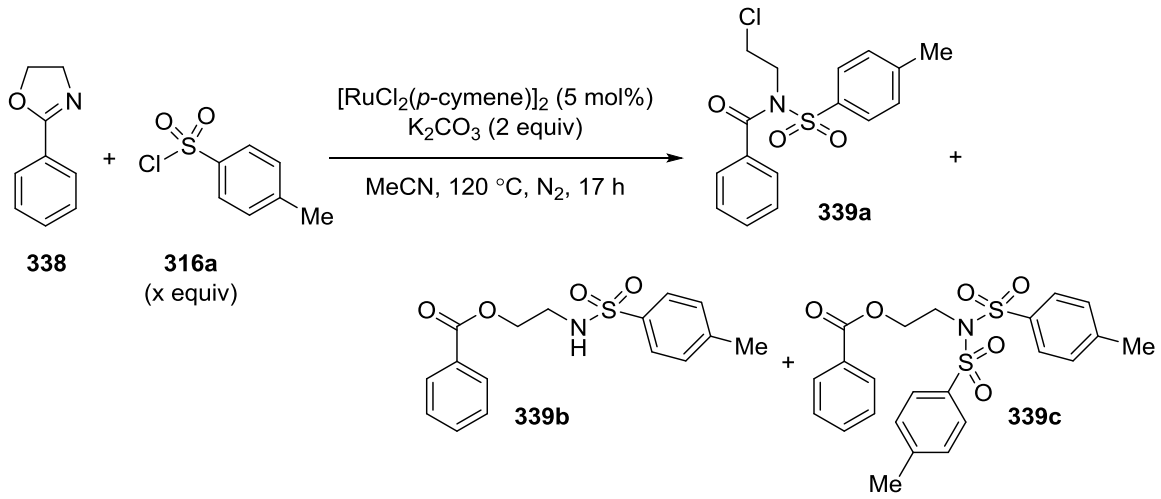
Scheme 130

According to the literature, the direction of the ring-opening is influenced by the solvent used. The oxazoline ring can undergo hydrolysis under acidic or basic conditions. In addition, the ring-opening of the oxazoline could be performed solely in a solvent under thermal conditions.[74]

At present, there is a lot of literature on the ring-opening of oxazolines, but this methodology is mainly used in polymerisation.[75] Moreover, none of the studies in the literature have reported the use of sulfonyl chloride for the ring-opening of oxazoline compounds.[76] Diverging from the main focus on C-H functionalisation, it was decided to investigate the ring-opening reaction of 2-phenyl-2-oxazoline because the products formed in this reaction could have a lot of potential applications and be used for further transformations, such as sulfonamides which are widely used in drug targets.[37, 77]

The first task was to optimise the reaction. The stoichiometric ratio of *p*-TsCl with 2-phenyl-2-oxazoline was examined. Interestingly when the amount of *p*-TsCl is reduced to less than 2 equivalents, no **339a** was formed (Table 20, entries 2 & 3). In both cases, the yield of the disulfonamide **339c** has been reduced. From the results it was decided to use 1.5 equivalents of *p*-TsCl for the optimisation study.

Table 20. Effects of *p*-TsCl equivalence on the ring-opening of 2-phenyl-2-oxazaline

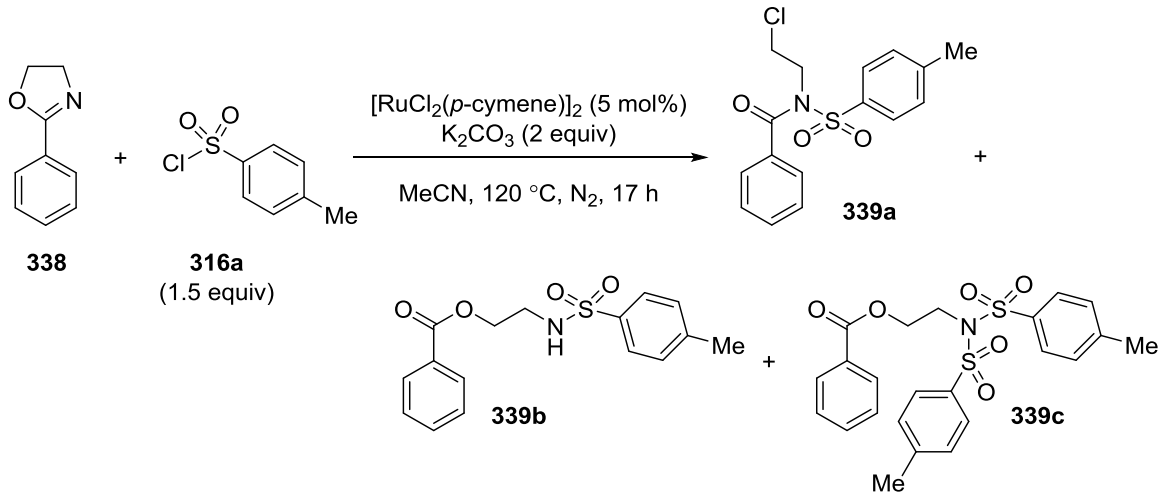


entry[a]	*p*-TsCl (equiv)	**339a** yield (%)[c]	**339b** yield (%)[c]	**339c** yield (%)[c]	SM yield (%)[c]
1	3	1[b]	54[b]	15[b]	-
2	1.5	0	traces	3	26
3	1	0	traces	2	90

[a]Reaction conditions: $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), 2-phenyl-2-oxazoline (1.5 mmol), *p*-TsCl (x equiv), MeCN (3 mL), 120 °C, N_2. [b]Isolated yields. [c] ^{1}H NMR conversions (%).

The literature notes that oxazolines can undergo ring-opening under thermal conditions without the need of any catalysts or base present. Therefore, the effects of the catalyst and base were investigated to see if the presence of a catalyst or base will facilitate the ring-opening reaction or not (Table 21). Interestingly, in the absence of either the base or catalyst under thermal conditions none of the di-sulfonamide **339c** was formed and produced only the chloro **339a** and the mono-sulfonamide product **339b**.

Table 21. Effects of the presence of catalyst and base on the ring-opening of 2-phenyl-2-oxazoline

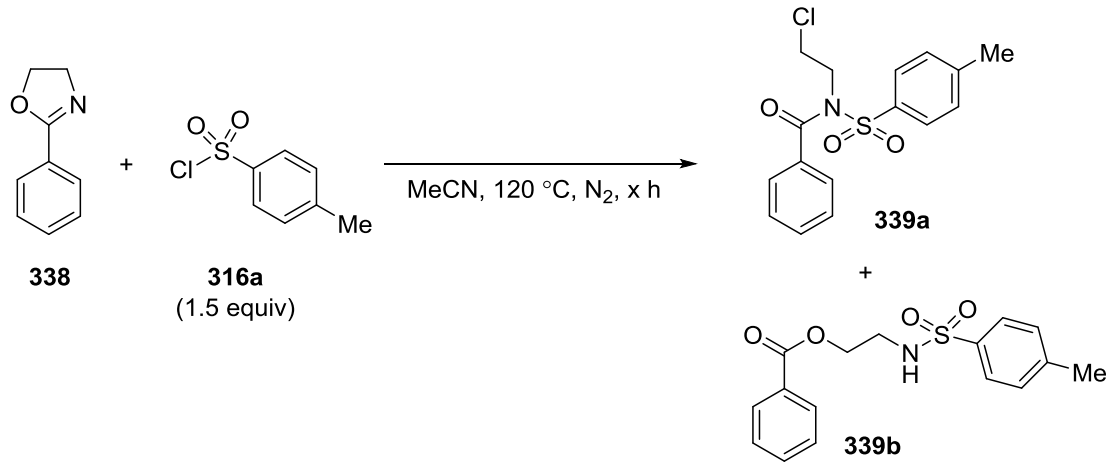


entry	base	catalyst	**339a** yield (%)[b]	**339b** yield (%)[b]	**339c** yield (%)[b]	SM yield (%)[b]
1	no	yes	88	12	0	0
2	yes	no	66	8	0	26

[a]Reaction conditions: $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (2 equiv), 2-phenyl-2-oxazoline (1.5 mmol), *p*-TsCl (2.3 mmol), MeCN (3 mL), 120 °C, N_2. [b] ^1H NMR conversion (%).

A dilemma arose as to how the oxazoline ring-open occurred in the absence of water to form the two sulfonamide products. It is possible that the formation of the ester moiety was the result of quenching the reaction with water. Meaning as soon as the water is added to the reaction mixture to quench the reaction, water neutralises the charge on the nitrogen and leads to the ring-opening of oxazoline. So two reactions were performed and stopped after 2 and 8 hours respectively (Table 22). In both cases the reaction was not quenched with water; instead the solvent was removed under vacuum. From the crude ^1H NMR spectrum, the conversion was calculated for each product formed as well as the starting material present. Surprisingly after 2 hours of reflux, the reaction mixture was close to completion; only 9% of starting material remained (Table 22, entry 1). In both cases, the chloro product **339a** was formed as the major product. In addition from the ^1H NMR spectrum of mono-sulfonamide **339b** an unknown compound (**339d**) was observed which could not be separated from the product **339b**.

Table 22. Reaction stopped at different times for the ring-opening of 2-phenyl-2-oxazoline



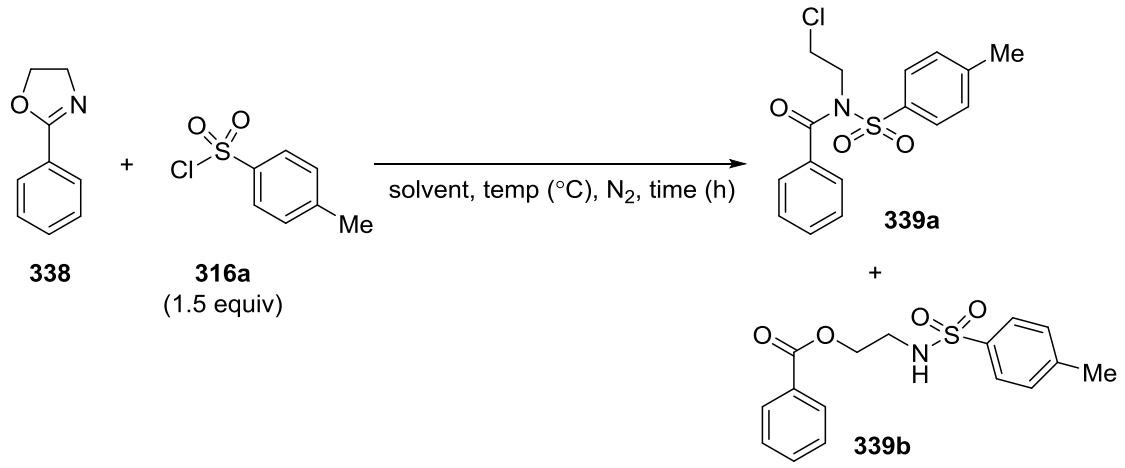
338 **316a** (1.5 equiv)

entry[a]	time (h)	**339a** yield (%)[b]	**339b** yield (%)[b]	SM yield (%)[b]
1	2	68	23[c]	9
2	8	85	14[c]	0

[a]Reaction conditions: 2-phenyl-2-oxazoline (1.5 mmol), *p*-TsCl (2.3 mmol), MeCN (3 mL), 120 °C, N_2. [b] ^{1}H NMR conversion (%). [c]As a mixture of **339b** with unknown denoted as **339d**.

A solvent screen was carried out, to investigate which solvent is most suitable for this reaction. All solvents used were anhydrous (Table 23). Interestingly at 140 °C only **339a** and **339b** were formed in the reaction, however at a lower temperature of 80 ^{o}C three products **339a**, **339b** and **339d** in 78%, 13% and 9% respectively (Table 23, entries 1 & 2). Changing the reaction time from 19 hours to 16 hours at 80 °C gave similar conversions, so the reaction time was reduced to 16 hours for the rest of the solvent screen (Table 23, entry 3). At a lower temperature of 60 °C, the ratio between **339a**:**339b** decreases slightly and the coversion of **339d** increases to 18%. After lowering the temperature to 40 °C the **339a** and **339b** were formed in similar conversions (Table 23, entry 5). Reaction in dichloromethane also provided **339a** and **339b** with similar conversions (Table 23, entry 7). At room temperature, the reaction is sluggish and the conversions were poor (Table 23, entry 6). Toluene was found to be incompatible for the ring-opening reaction as there was 24% of starting materials not consumed in the reaction (Table 23, entry 9).

Table 23. Solvent screen of the ring-opening of 2-phenyl-2-oxazoline

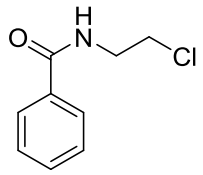


entry[a]	solvent	temp (°C)	time (h)	**339a** (%)[b]	**339b** (%)[b]	**339d** (%)[b]	SM (%)[b]
1	MeCN	140	19	86	14	0	0
2	MeCN	80	19	78	13	9	0
3	MeCN	80	16	73	12	12	0[c]
4	MeCN	60	16	59	23	18	0
5	MeCN	40	16	39	32	29	0
6	MeCN	rt	90	34	14	14	38
7	dichloromethane	40	16	28	30	29	13
8	THF	60	16	9	41	50	0
9	toluene	60	16	42	17	17	24
10	acetone	60	16	8	50	42	0
11	DMF	60	16	0	0	85	15[f]

[a]Reaction conditions: 2-phenyl-2-oxazoline (1.5 mmol), *p*-TsCl (2.3 mmol) MeCN (3 mL), 120 °C, N_2. [b] ^{1}H NMR conversion (%). [c] 3% of **339c** present. Acetone was distilled and dried over potassium carbonate.

An interesting finding is that for the ring-opening reaction in either acetone or MeCN the ratios of **339a** to **339b** exchanges, in MeCN it favours the formation of **339a** as the major product. In contrast, acetone seems to favour the formation of **339b** (Table 23, entry 10). From the results, it shows that depending on the reaction solvent it determines the outcome of which oxazoline ring-opened product is obtained.

The reaction in DMF gave **339d** as the only product exclusively (Table 23, entry 11) and elucidation of the compound by spectroscopic analysis using 1D and 2D ^{1}H and ^{13}C NMR spectroscopy revealed compound **339d** as ring-opened an oxazoline with a chlorine atom on the alkyl chain (Scheme 131).



339d

Scheme 131

From this optimisation study, it was discovered that treatment of 2-phenyl-2-oxazoline **339** with *p*-TsCl **316a** under certain conditions, could obtain different ring-opened products. The absence of $[RuCl_2(p\text{-cymene})]_2$ or K_2CO_3 eliminates the formation of **339c**. Depending on the reaction solvent, it can shift the ratio of the products **339a** and **339b** formed. In addition, it was revealed that in the absence of base and catalyst, another product could be formed from the oxazoline ring-opening reaction, which was denoted as **339d**. This compound **339d** have a similar R_f values to **339b**, making it hard to separate in purification *via* column chromatography. Fortunately, when the reaction medium was switched to DMF, **339d** was isolated as the sole product in the reaction and the structure was able to be confirmed by spectroscopic analysis.

2.4.3. Conclusions

An optimisation study was performed to attempt to optimise the *meta*-sulfonation reaction of 2-phenylpyridine with *p*-TsCl. From the optimisation study, it was revealed that the order of reagent addition has a large influence on the product yield. A study on the scope of the *meta*-sulfonation was performed with 2-phenylpyrdine and it was highlighted that this reaction is limited to arylsulfonyl chlorides only. In addition, by adding substituents to the 2-phenylpyridine substrate it has an impact on the yields as well. More importantly, having a *meta*-substituent on the substrate, shuts the reaction down, which suggests the reaction is *via para* activation, where the Ru-C bond is *para*-directing to give the *meta*-sulfonated product.

A substrate scope was performed and found that only phenylpyrazole and benzo[*h*]quinoline work under the *meta*-sulfonation conditions, albeit with poor yields. Attempts to optimise the *meta*-sulfonation of 1-phenylpyrazole and benzo[*h*]quinoline gave no improvement upon the standard conditions. In addition, it was discovered that in the presence of an oxazoline and *p*-TsCl, the oxazoline moiety undergoes ring-opening to give several products.

2.5. References

1. L. C. Campeau and K. Fagnou, *Chem. Commun.*, 2006, 1253-1264.
2. I. V. Seregin and V. Gevorgyan, *Chem. Soc. Rev.*, 2007, **36**, 1173-1193.
3. F. Kakiuchi and T. Kochi, *Synthesis*, 2008, 3013-3039.
4. O. Daugulis, H.-Q. Do and D. Shabashov, *Acc. Chem. Res.*, 2009, **42**, 1074-1086.
5. Y. Zhou, J. Zhao and L. Liu, *Angew. Chem. Int. Ed.*, 2009, **48**, 7126-7128.
6. T. Truong and O. Daugulis, *Angew. Chem. Int. Ed.*, 2012, **51**, 11677-11679.
7. J. Y. Cho, M. K. Tse, D. Holmes, R. E. Maleczka and M. R. Smith, *Science*, 2002, **295**, 305-308.
8. J. M. Murphy, X. Liao and J. F. Hartwig, *J. Am. Chem. Soc.*, 2007, **129**, 15434-15435.
9. D. W. Robbins and J. F. Hartwig, *Angew. Chem. Int. Ed.*, 2013, **52**, 933-937.
10. R. J. Phipps and M. J. Gaunt, *Science*, 2009, **323**, 1593-1597.
11. H. A. Duong, R. E. Gilligan, M. L. Cooke, R. J. Phipps and M. J. Gaunt, *Angew. Chem. Int. Ed.*, 2011, **50**, 463-466.
12. B. Chen, X. L. Hou, Y. X. Li and Y. D. Wu, *J. Am. Chem. Soc.*, 2011, **133**, 7668-7671.
13. D. Lapointe and K. Fagnou, *Chem. Lett.*, 2010, **39**, 1119-1126.
14. Y.-H. Zhang, B.-F. Shi and J.-Q. Yu, *J. Am. Chem. Soc.*, 2009, **131**, 5072-5074.
15. S. L. Zhang, L. Shi and Y. Q. Ding, *J. Am. Chem. Soc.*, 2011, **133**, 20218-20229.
16. X. F. Cong, H. R. Tang, C. Wu and H. M. Zeng, *Organometallics*, 2013, **32**, 6565-6575.
17. D. Leow, G. Li, T. S. Mei and J. Q. Yu, *Nature*, 2012, **486**, 518-522.
18. R. Beesley, C. Ingold and J. Thorpe, *J. Chem. Soc. Trans.*, 1915, **107**, 1080-1106.
19. C. K. Ingold, *J. Chem. Soc. Trans.*, 1921, **119**, 305-329.
20. P. V. Schleyer, *J. Am. Chem. Soc.*, 1961, **83**, 1368-1373.
21. M. E. Jung and J. Gervay, *J. Am. Chem. Soc.*, 1991, **113**, 224-232.
22. Y. F. Yang, G. J. Cheng, P. Liu, D. Leow, T. Y. Sun, P. Chen, X. H. Zhang, J. Q. Yu, Y. D. Wu and K. N. Houk, *J. Am. Chem. Soc.*, 2014, **136**, 344-355.
23. H. X. Dai, G. Li, X. G. Zhang, A. F. Stepan and J. Q. Yu, *J. Am. Chem. Soc.*, 2013, **135**, 7567-7571.
24. L. Wan, N. Dastbaravardeh, G. Li and J. Q. Yu, *J. Am. Chem. Soc.*, 2013, **135**, 18056-18059.
25. G. J. Cheng, Y. F. Yang, P. Liu, P. Chen, T. Y. Sun, G. Li, X. H. Zhang, K. N. Houk, J. Q. Yu and Y. D. Wu, *J. Am. Chem. Soc.*, 2014, **136**, 894-897.
26. R. Y. Tang, G. Li and J. Q. Yu, *Nature*, 2014, **507**, 215-220.
27. G. Q. Yang, P. Lindovska, D. J. Zhu, J. Kim, P. Wang, R. Y. Tang, M. Movassaghi and J. Q. Yu, *J. Am. Chem. Soc.*, 2014, **136**, 10807-10813.
28. S. Lee, H. Lee and K. L. Tan, *J. Am. Chem. Soc.*, 2013, **135**, 18778-18781.
29. J. Cornella, M. Righi and I. Larrosa, *Angew. Chem. Int. Ed.*, 2011, **50**, 9429-9432.
30. J. F. Luo, S. Preciado and I. Larrosa, *J. Am. Chem. Soc.*, 2014, **136**, 4109-4112.
31. L. Ackermann, R. Vicente and A. R. Kapdi, *Angew. Chem. Int. Ed.*, 2009, **48**, 9792-9826.
32. C. Y. Lee, S. J. Ahn and C. H. Cheon, *J. Org. Chem.*, 2013, **78**, 12154-12160.
33. X. Zhao, E. Dimitrijevic and V. M. Dong, *J. Am. Chem. Soc.*, 2009, **131**, 3466-3467.
34. N. Neamati, A. Mazumder, H. Zhao, S. Sunder, T. R. Burke, R. J. Schultz and Y. Pommier, *Antimicrob. Agents Chemother.*, 1997, **41**, 385-393.
35. D. C. Meadows and J. Gervay-Hague, *Med Res Rev*, 2006, **26**, 793-814.

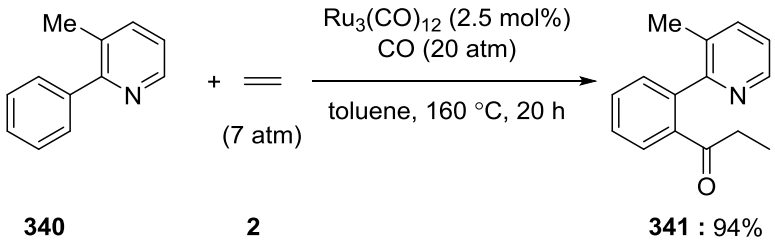
36. X. L. Yan, Z. L. Wang, A. Sudom, M. Cardozo, M. DeGraffenreid, Y. M. Di, P. C. Fan, X. A. He, J. C. Jaen, M. Labelle, J. S. Liu, J. Ma, D. McMinn, S. C. Miao, D. Q. Sun, L. A. Tang, H. Tu, S. Ursu, N. Walker, Q. P. Ye and J. P. Powers, *Bioorg. Med. Chem.*, 2010, **20**, 7071-7075.
37. H. X. Dai, A. F. Stepan, M. S. Plummer, Y. H. Zhang and J. Q. Yu, *J. Am. Chem. Soc.*, 2011, **133**, 7222-7228.
38. S. Y. Woo, J. H. Kim, M. K. Moon, S. H. Han, S. K. Yeon, J. W. Choi, B. K. Jang, H. J. Song, Y. G. Kang, J. W. Kim, J. Lee, D. J. Kim, O. Hwang and K. D. Park, *J. Med. Chem.*, 2014, **57**, 1473-1487.
39. O. Saidi, J. Marafie, A. E. W. Ledger, P. M. Liu, M. F. Mahon, G. Kociok-Kohn, M. K. Whittlesey and C. G. Frost, *J. Am. Chem. Soc.*, 2011, **133**, 19298-19301.
40. A. M. Clark, C. E. F. Rickard, W. R. Roper and L. J. Wright, *Organometallics*, 1999, **18**, 2813-2820.
41. M. Gagliardo, D. J. M. Snelders, P. A. Chase, R. J. M. K. Gebbink, G. R. M. van Klink and G. van Koten, *Angew. Chem. Int. Ed.*, 2007, **46**, 8558-8573.
42. D. L. Davies, O. Al-Duaij, J. Fawcett, M. Giardiello, S. T. Hilton and D. R. Russell, *Dalton Trans.*, 2003, 4132-4138.
43. B. Li, T. Roisnel, C. Darcel and P. H. Dixneuf, *Dalton Trans.*, 2012, **41**, 10934-10937.
44. Y. Boutadla, D. L. Davies, R. C. Jones and K. Singh, *Chem. Eur. J.*, 2011, **17**, 3438-3448.
45. I. Ozdemir, S. Demir, B. Cetinkaya, C. Gourlaouen, F. Maseras, C. Bruneau and P. H. Dixneuf, *J. Am. Chem. Soc.*, 2008, **130**, 1156-1157.
46. L. Ackermann, R. Vicente, H. K. Potukuchi and V. Pirovano, *Org. Lett.*, 2010, **12**, 5032-5035.
47. L. Ackermann, *Chem. Rev.*, 2011, **111**, 1315-1345.
48. S. Fernandez, M. Pfeffer, V. Ritleng and C. Sirlin, *Organometallics*, 1999, **18**, 2390-2394.
49. J. Matthes, S. Grundemann, A. Toner, Y. Guari, B. Donnadieu, J. Spandl, S. Sabo-Etienne, E. Clot, H. H. Limbach and B. Chaudret, *Organometallics*, 2004, **23**, 1424-1433.
50. K. Cheng, B. B. Yao, J. L. Zhao and Y. H. Zhang, *Org. Lett.*, 2008, **10**, 5309-5312.
51. Y. K. Liu, S. J. Lou, D. Q. Xu and Z. Y. Xu, *Chem. Eur. J.*, 2010, **16**, 13590-13593.
52. S. J. Lou, D. Q. Xu, A. B. Xia, Y. F. Wang, Y. K. Liu, X. H. Du and Z. Y. Xu, *Chem. Commun.*, 2013, **49**, 6218-6220.
53. X. Chen, X. S. Hao, C. E. Goodhue and J. Q. Yu, *J. Am. Chem. Soc.*, 2006, **128**, 6790-6791.
54. Y. Li, X. S. Zhang, K. Chen, K. H. He, F. Pan, B. J. Li and Z. J. Shi, *Org. Lett.*, 2012, **14**, 636-639.
55. F. Xie, Z. S. Qi and X. W. Li, *Angew. Chem. Int. Ed.*, 2013, **52**, 11862-11866.
56. S. Fustero, M. Sanchez-Rosello, P. Barrio and A. Simon-Fuentes, *Chem. Rev.*, 2011, **111**, 6984-7034.
57. Y. L. Janin, *Chem. Rev.*, 2012, **112**, 3924-3958.
58. X. W. Li, S. J. Yu, F. Wang, B. S. Wan and X. Z. Yu, *Angew. Chem. Int. Ed.*, 2013, **52**, 2577-2580.
59. L. B. Huang, Q. Wang, J. Qi, X. Wu, K. F. Huang and H. F. Jiang, *Chem. Sci.*, 2013, **4**, 2665-2669.
60. F. Pan, Z. Q. Lei, H. Wang, H. Li, J. Sun and Z. J. Shi, *Angew. Chem. Int. Ed.*, 2013, **52**, 2063-2067.
61. Y. Hashimoto, T. Ueyama, T. Fukutani, K. Hirano, T. Satoh and M. Miura, *Chem. Lett.*, 2011, **40**, 1165-1166.
62. L. Ackermann, S. I. Kozhushkov and D. S. Yufit, *Chem. Eur. J.*, 2012, **18**, 12068-12077.
63. Y. Hashimoto, K. Hirano, T. Satoh, F. Kakiuchi and M. Miura, *J. Org. Chem.*, 2013, **78**, 638-646.
64. X. Zhao and V. M. Dong, *Angew. Chem. Int. Ed.*, 2011, **50**, 932-934.
65. S. Oi, E. Aizawa, Y. Ogino and Y. Inoue, *J. Org. Chem.*, 2005, **70**, 3113-3119.
66. L. Ackermann, A. Althammer and R. Born, *Angew. Chem. Int. Ed.*, 2006, **45**, 2619-2622.
67. S. Oi, H. Sasamoto, R. Funayama and Y. Inoue, *Chem. Lett.*, 2008, **37**, 994-995.

68. S. Oi, R. Funayama, T. Hattori and Y. Inoue, *Tetrahedron*, 2008, **64**, 6051-6059.
69. S. Oi, H. Sato, S. Sugawara and Y. Inoue, *Org. Lett.*, 2008, **10**, 1823-1826.
70. L. Ackermann, R. Vicente and A. Althammer, *Org. Lett.*, 2008, **10**, 2299-2302.
71. L. Ackermann, J. Pospech and H. K. Potukuchi, *Org. Lett.*, 2012, **14**, 2146-2149.
72. A. A. Goldberg and W. Kelly, *J. Chem. Soc.*, 1948, 1919-1926.
73. E. M. Fry, *J. Org. Chem.*, 1950, **15**, 802-806.
74. D. A. Tomalia and J. N. Paige, *J. Org. Chem.*, 1973, **38**, 422-430.
75. J. Luston, J. Kronek and I. Janigova, *J. Macromol. Sci. Pure*, 2010, **47**, 716-724.
76. T. G. Gant and A. I. Meyers, *Tetrahedron*, 1994, **50**, 2297-2360.
77. M. Aggarwal, B. Kondeti and R. McKenna, *Bioorg. Med. Chem.*, 2013, **21**, 1526-1533.

Chapter 3. C-H acylation

3.1.1. C-H acylation *via* carbonylation

The carbonyl moiety is found in many medicinal compounds and the ability to selectively introduce the carbonyl functionality into aromatic rings is a valuable tool for organic synthesis. Traditionally aryl ketones are prepared by Friedel-Crafts acylation reactions, in which aromatic compounds are treated with acyl chlorides in the presence of stoichiometric amounts of Lewis acids such as $AlCl_3$, $FeCl_3$ and $SnCl_4$, to provide the acylated arenes. However, there is an issue with the regioselectivity of the products obtained by this method, because the substituents on the aromatic ring have a major influence on the outcome of the product, which means certain functional groups need to be installed beforehand to perform the Friedel-Crafts acylation. This problem can be resolved by employing a transition metal complex to selectively activate a C-H bond in the molecule, to form a metallacycle.[1, 2] The activated C-H bond is much more reactive than the sp^2 C-H bond, which can be converted to a functionalised carbon bond; this process is known as C-H functionalisation.[3-5] One of the benefits of utilising C-H functionalisation, is that the regioselectivity of the product can be controlled by utilising a chelating group, which directs the incoming electrophile in place of the carbon-metal bond, to provide the *ortho* or *meta*-C-H functionalised product. This method is much more efficient than traditional aromatic chemistry such as S_EAr, as the reaction is performed with only a catalytic amount of the transition metal. Since the emergence of transition-metal catalysed direct C-H functionalisation, a number of strategies have been developed to achieve C-H acylation.[6] One example is the *ortho*-C-H carbonylation reaction, which is a three-component reaction that involves arene, carbon monoxide and olefins.[7-13] This reaction has been studied extensively and provides aliphatic ketones as products. One example is developed by Murai employing $Ru_3(CO)_{12}$ as the catalyst, reaction of **340** with ethylene and carbon monoxide in toluene at 160 °C gave the corresponding product **341** in 94% yield (Scheme 132).[8]

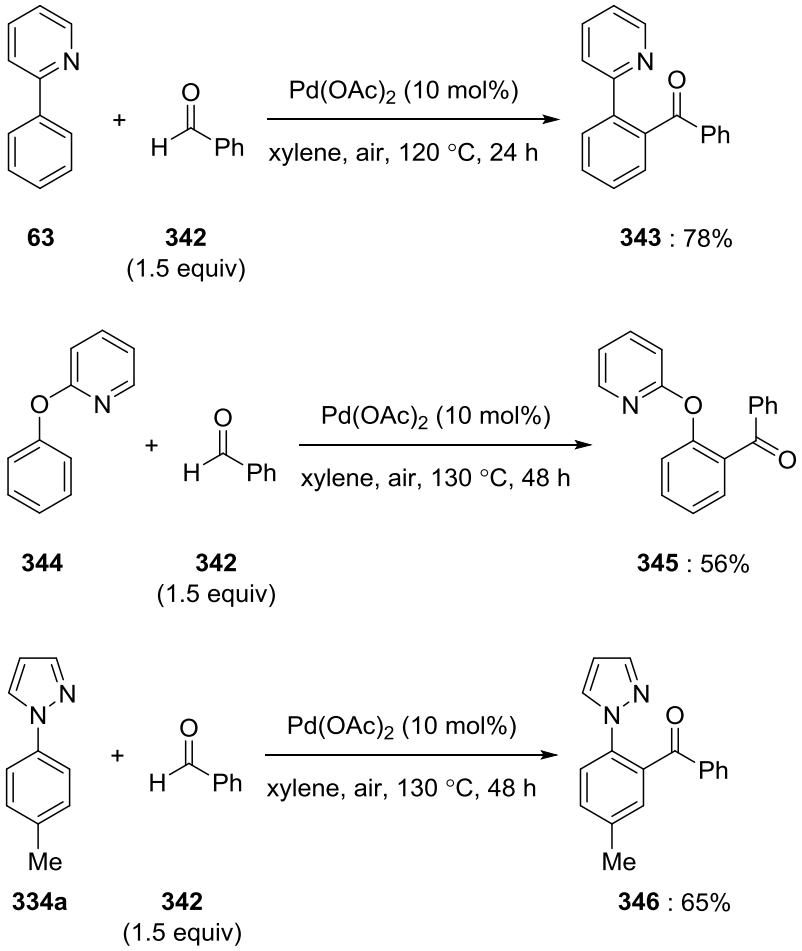


340 **2** **341** : 94%

Scheme 132

3.1.2. C-H acylation *via* oxidation

Other methods to accomplish acylation by C-H bond cleavage can be achieved by employing aldehydes, alcohols or toluene in the presence of an oxidising agent, these methods usually employ a Pd or Rh catalyst to perform the transformation.[6, 14-37] In 2009, Cheng *et al.* utilised $Pd(OAc)_2$ to acylate arylpyridine derivatives with aldehydes in the presence of air as the oxidising agent, in xylene at 120 °C for 24 hours.[14] Other substrates such as 2-aryloxypyridine **344** and phenylpyrazole **334a** required longer reaction times to achieve satisfactory yields (Scheme 133).

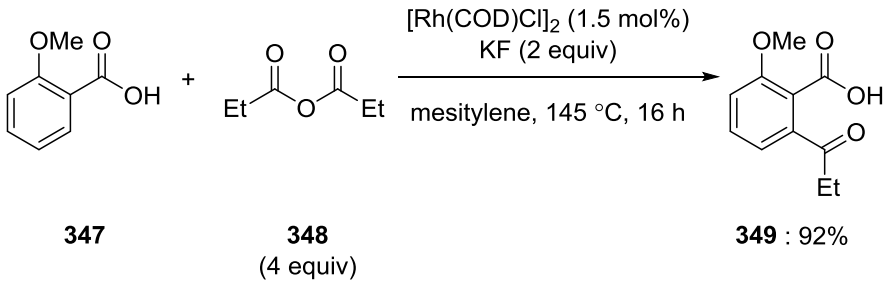


Scheme 133

3.1.3. C-H acylation *via* coupling with anhydrides

In 2013 Gooβen *et al.* described a rhodium-catalysed acylation of aromatic carboxylic acids with anhydrides as the coupling partner (Scheme 134).[38] The reaction is compatible with a range of anhydrides and both aliphatic and aryl products can be formed. In addition, various functional

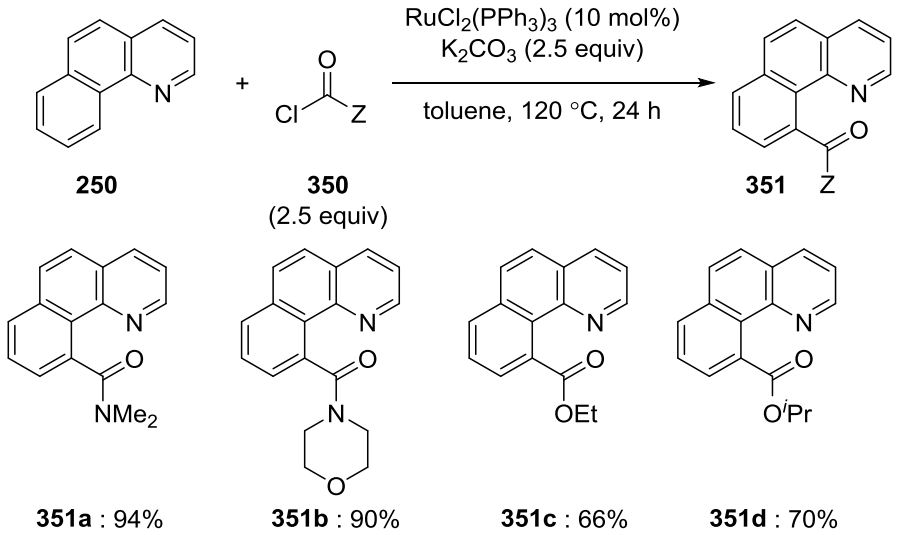
groups such as OMe, NMe_2, OH, ketone, F, Cl, Br and CF_3 were all tolerated in the reaction. Only the monoacylated product was afforded in the reactions, however it is noteworthy that benzoic acid was not employed in the study.



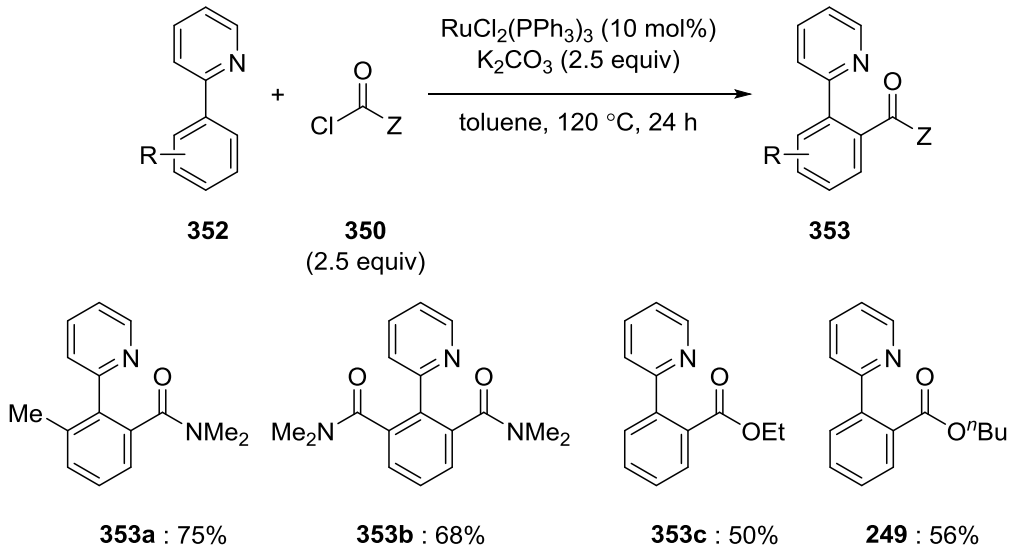
Scheme 134

3.1.4. C-H acylation *via* coupling with chloroformates and alkyl carbamoyl chlorides

Alternatively, chloroformates and alkyl carbamoyl chlorides can be used as acylating reagents in the absence of an oxidant. In 2009, Kakiuchi *et al.* developed the first example of transition-metal catalysed introduction of amide and ester groups' *via* C-H bond functionalisation using chlorocarbonyl compounds.[39] 2-Phenylpyridine and benzo[*h*]quinoline were employed as substrates in this study with various carbamoyl chlorides and chloroformates. Interestingly, for both substrates, C-H aminocarbonylation appears to be more efficient than the C-H alkoxycarbonylations of phenylpyridine and benzo[*h*]quinoline, as the amide products were synthesised in better yields (Schemes 135 and 136).



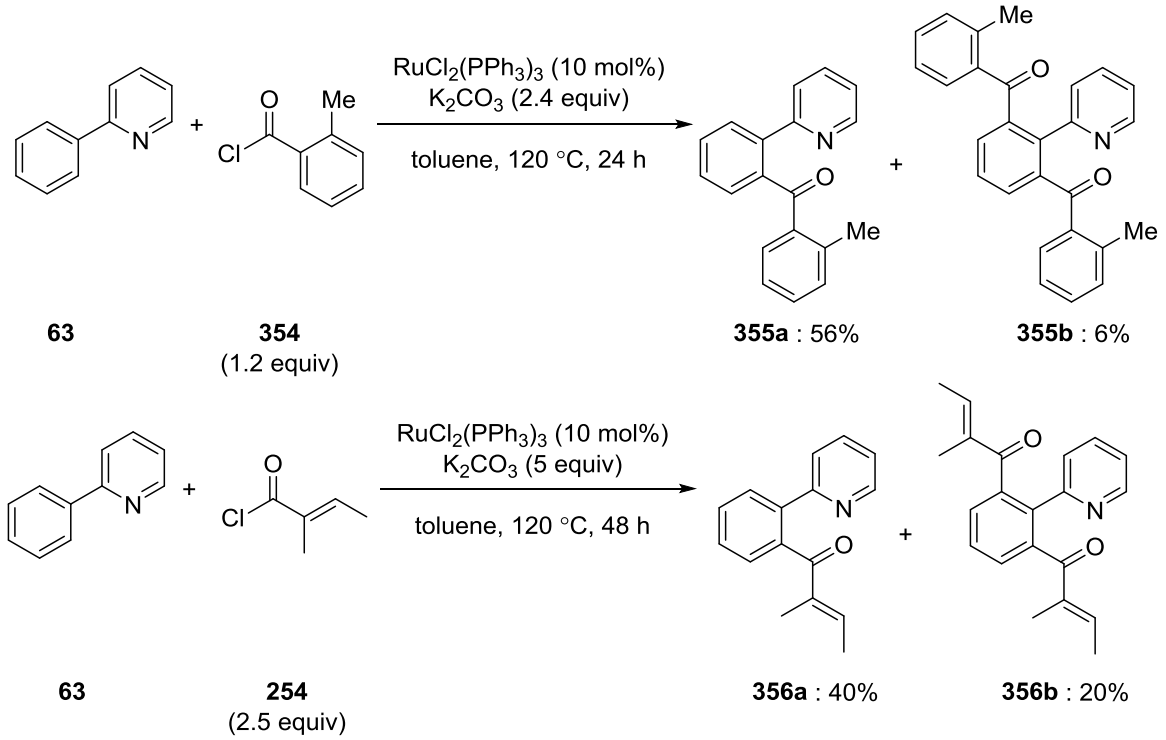
Scheme 135



Scheme 136

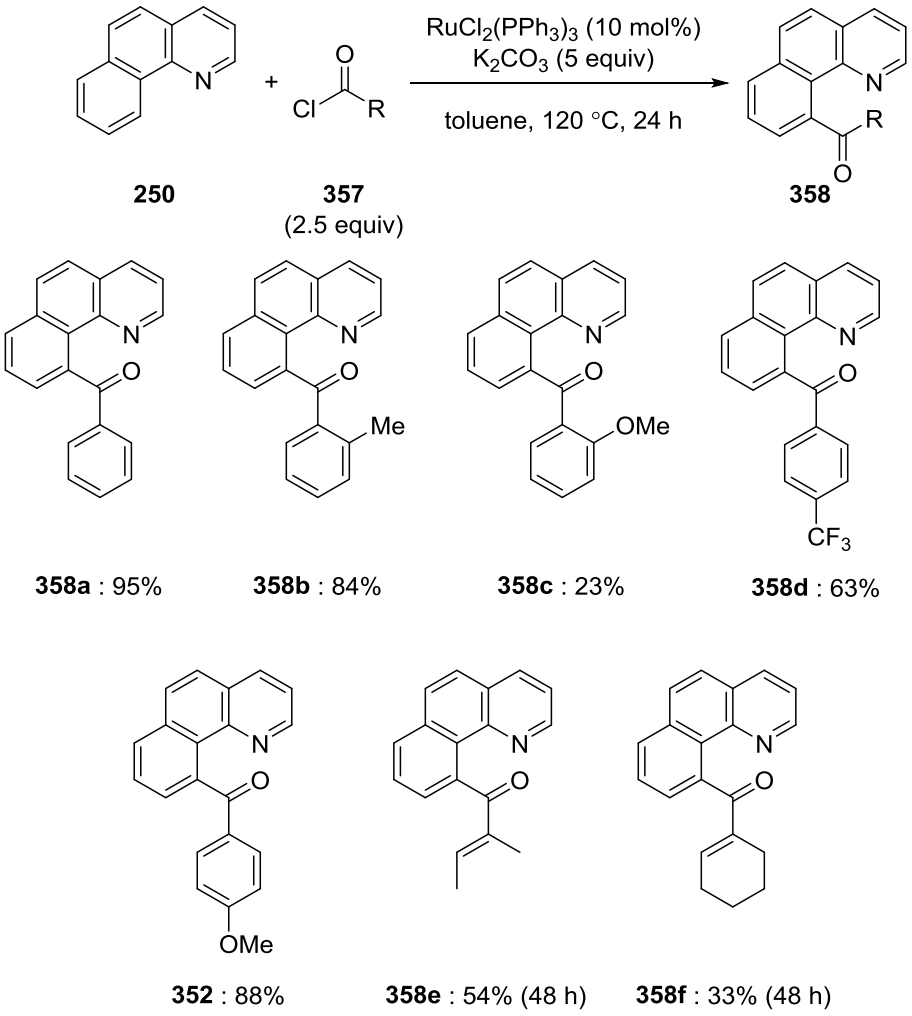
3.1.5. C-H acylation *via* coupling with acid chlorides

In 2011, Kakiuchi also reported employing acyl chlorides as the acylating reagent, using the same ruthenium(II) catalyst, $RuCl_2(PPh_3)_3$.[40] Treatment of 2-phenylpyridine with *ortho*-toluoyl chloride in the presence of 10 mol% of $RuCl_2(PPh_3)_3$ and 5 equivalents of base K_2CO_3 in toluene and heated at 120 °C for 24 hours afforded the *ortho*-acylated product **355a** in 56% yield and 6% of the diacylated product **355b**. Unfortunately the substrate scope was not studied in-depth, *meta*-Me and *meta*-CF_3 substituted 2-phenylpyridines were compatible substrates. On the other hand, a substrate containing a *para*-F substituent proved to be unreactive. In addition, reaction with *trans*-2-methyl-2-butenoyl chloride **254** required not only higher stoichiometry of K_2CO_3 and acid chloride, but also an extended reaction time (Scheme 137).



Scheme 137

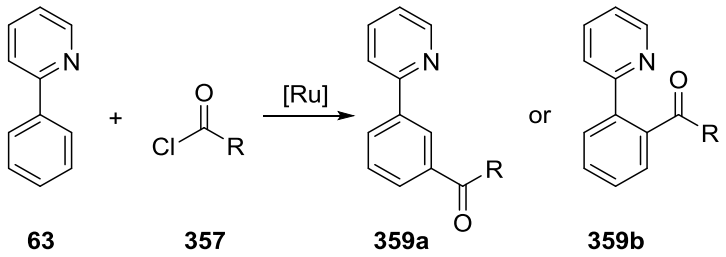
Benzo[*h*]quinoline **250** showed higher reactivity compared to 2-phenylpyridine **63**, as there was a broader scope of acid chlorides explored. Aryl and olefinated acid chlorides were compatible coupling partners and provided the corresponding products in good yields (Scheme 138).



Scheme 138

3.2. Aims and objectives

This chapter explores the utility of acyl chlorides as electrophiles to perform sp^2 C-H functionalisation of heteroaromatics *via* Ru(II) catalysis. Based on our previous studies, the use of ruthenium(II) catalyst $[RuCl_2(p\text{-cymene})]_2$ enabled the C-H sulfonation of 2-phenylpyridine to take place on the *meta* C-H site, *via* a remote *para* activation mechanism. It was hypothesised that two possible products, arising from acylation at either the *ortho* or *meta* position, could be obtained, depending on the reaction mechanism of the C-H acylation (Scheme 139). If the mechanism involves the σ-activation pathway followed by electrophilic attack of the acid chloride, it would produce the *meta*-acylated product **359a**. Contrastingly, a mechanism involving chelation-assisted cyclometallation followed by oxidative addition of the acid chloride would provide the *ortho*-acylated product **359b**.

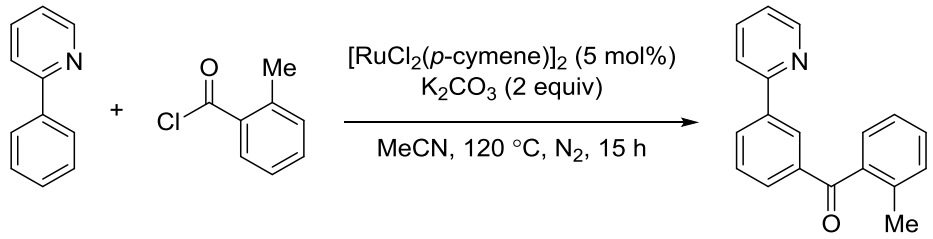


Scheme 139

3.3.1. Results and discussion

3.3.1a. Ru(II)-catalysed C-H acylation of 2-phenylpyridine

It has been known that if a pyridine is subjected to Friedel-Crafts acylation , the acyl group will be introduced at C4 on the pyridine ring. However, if 2-phenylpyridine is reacted with an acid chloride under our *meta*-sulfonation conditions described in chapter 2, it was hypothesised that the regioselectivity of the product will be different from the product expected for a Friedel-Crafts reaction and might furnish the *meta*-acylated product **360**. *Ortho*-toluoyl chloride was chosen as the acylating reagent, since it has been shown to be an efficient coupling partner in the work by Kakiuchi,[40] as well as the presence of the methyl group which would aid the interpretation of the crude ^{1}H NMR spectrum for any signs of product formation. Treatment of 2-phenylpyridine **63** with 3 equivalents of *ortho*-toluoyl chloride **354** in the presence of 5 mol% of $[RuCl_2(p\text{-cymene})]_2$ and 2 equivalents of K_2CO_3 in dry MeCN was heated at 120 °C, unfortunately after 15 hours of heating no products were observed (Scheme 140).

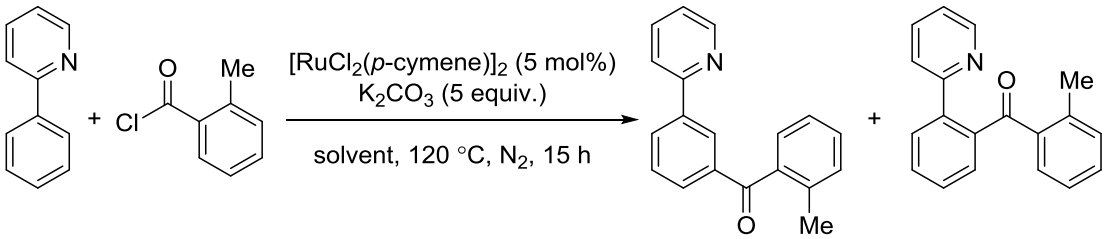


Scheme 140

Although the reaction did not work, it was decided to pursue C-H acylation of 2-phenylpyridine utilising $[RuCl_2(p\text{-cymene})]_2$ as the catalyst and expand the reaction conditions to see if acylation could be achieved. Kakiuchi's study on C-H acylation employed 2.4 to 5 equivalents of K_2CO_3 in

their catalyst system and the stoichiometry of the acylating reagent employed is from 1.2 to 2.5 equivalents. Taking this into account, it was decided to use 5 equivalents of base and 2.5 equivalents of the acylating reagent. The first optimisation was the reaction solvent. Various solvents were examined for the reaction of 2-phenylpyridine **63** with *ortho*-toluoyl chloride **354**, utilising 5 mol% of $[RuCl_2(p\text{-cymene})]_2$ and 5 equivalents of K_2CO_3 as the catalyst system (Table 24). From the solvent screen, MeCN, THF and EtOAc gave no product (Table 24, entries 1, 2 & 4). But in 1,4-dioxane traces of new products were observed in the crude ^1H NMR spectrum (Table 24, entry 3). Reaction in toluene formed a product, but it was not the desired *meta*-acylated product, instead the *ortho*-monoacylated product was formed in 18% yield (Table 24, entry 5), which is considerably lower than the yield obtained under Kakiuchi's conditions. Although the product obtained was not the desired *meta*-acylated product, it was proposed that making changes to the catalyst system, the reaction pathway could be switched.

Table 24. Solvent screen of ruthenium catalysed C-H acylation of 2-phenylpyridine



63 **354** (2.5 equiv) **360** **355a** (lit: 56%)

entry[a]	solvent	**360** yield (%)[b]	**355a** yield (%)[b]
1	MeCN	-	-
2	THF	-	-
3	1,4-dioxane	-	traces
4	EtOAc	-	-
5	**toluene**	**-**	**18**

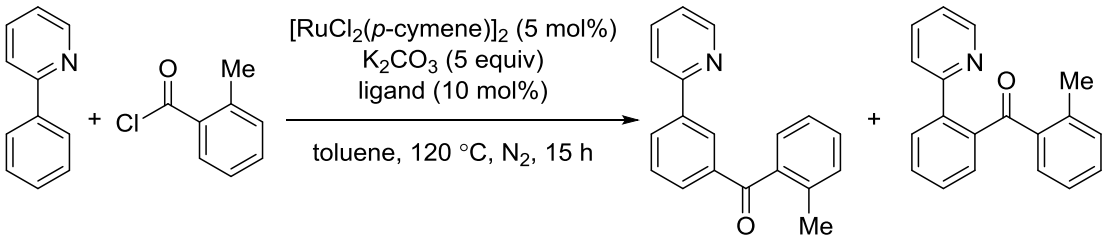
[a] Reaction conditions: 2-phenylpyridine (1.0 mmol), *ortho*-toluoyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (5 equivalents), solvent (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields.

The next variable under investigation was the addition of ligand to the catalyst system and 10 mol% of a variety of ligands were tested in the reaction (Table 25). Unfortunately, there were no *meta*-functionalised products detected, but some of the ligands again gave the *ortho*-acylated

product in good yield. From the results, it clearly highlights that bidentate or diphosphine ligands are not compatible in the present C-H acylation reaction and leads to hydolysis of the acid chloride to give the acid the 2-methylbenzoic acid **361** being formed (Scheme 141). Ligands such as diphenylphosphine ethane (DPPE), BINAP, Pybox and bipy were not suitable ligands and also formed the acid (Table 25, entries 1, 2, 8, 9 & 10). This behaviour could be ascribed to the steric bulk the bidentate ligands provide, as well as the cone angle, which is considerably larger than the monophosphine ligands, except for the case of DPPE, which has the smallest cone angle out of all of the ligands examined.[41-43] The anomalous result obtained for DPPE cannot be explained, it could be due to the electronics of the ligand or the fact that it's a bidentate ligand, which it could be occupying all of the available sites on the ruthenium centre, so cannot undergo oxidative addition with the acyl chloride to perform the acylation. Interestingly, ligands with a big cone angle are not suitable for the present C-H acylation such as SPhos with a cone angle of 240 ° (Table 25, entry 3).

Only three of the ligands examined facilitated the C-H acylation reaction, PPh_3, PCy_3 and $P(^tBu)_3$. PPh_3 provided the monoacylated product in 54% yield (Table 25, entry 4), but the more bulky P(*o*-tolyl)$_3$ only led to the formation of **361**(Table 25, entry 7). When the reaction was substituted with PCy_3 the yield of the monoacylated product was increased to 61% (Table 25, entry 5) and replacing the cyclohexane ligands from the phosphorus atom to ^{t}Bu groups, $P(^tBu)_3$ gave a lower yield of 19% product (Table 25, entry 6). From this observation, it suggests that the reaction is assisted by a steric acceleration effect as PCy_3 is considerably more bulky than PPh_3 and the cyclohexane ring can adopt different conformations. On the other hand, $P(^tBu)_3$ which has a larger cone angle exhibited poorer reactivity.

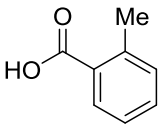
Table 25. Ligand screen of ruthenium catalysed C-H acylation of 2-phenylpyridine



63 **354** (2.5 equiv) **360** **355a** (lit: 56%)

entry[a]	ligand	Tolman cone angle (°)[44]	**360** yield (%)[b]	**355a** yield (%)[b]
1	DPPE	125	-	-[c]
2	S-BINAP	263	-	-[c]
3	SPhos	240	-	-
4	PPh_3	145	-	54
5	**PCy_3**	**170**	**-**	**61**
6	$P(^tBu)_3$	182	-	19
7	P(*o*-tolyl)$_3$	194	-	-[c]
8	Pybox		-	-[c]
9	bipy		-	-[c]
10	4,4'-dimethyl-bipyridyl		-	-[c]

[a] Reaction conditions: 2-phenylpyridine (1.0 mmol), *ortho*-toluoyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), ligand (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields. [c] **361**.



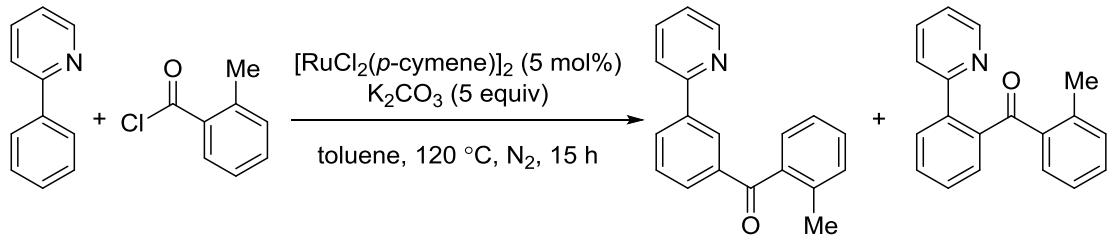
361

Scheme 141

Due to the formation of **361** found in the ligand screen, it was of interest to observe the effects of the presence of catalyst and base on the reaction (Table 26). As expected in the absence of

catalyst and base, no products were formed and 25% of **361** was formed (Table 26, entry 1). In the absence of the ruthenium catalyst, no products were formed other than **361** in 29% (Table 26, entry 2). In contrast, in the absence of the base there was 84% conversion of the acid formed (Table 26, entry 3). This clearly highlights the importance of excess base needed in the reaction; otherwise, the acid chloride would decompose to form the acid.

Table 26. Effects of catalyst and base on the ruthenium-catalysed C-H acylation of 2-phenylpyridine



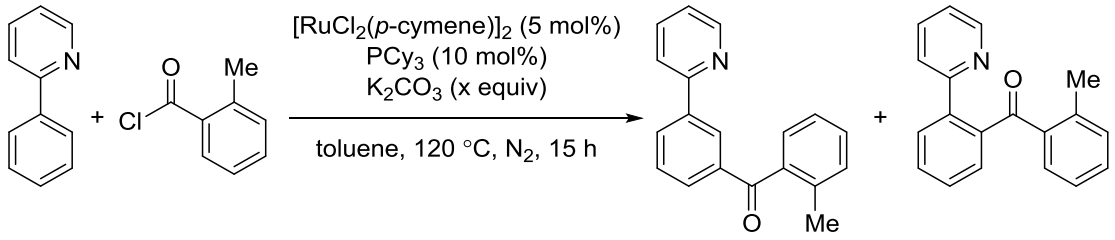
63 **354** (2.5 equiv) **360** **355a** (lit: 56%)

entry[a]	catalyst	base	**360** yield (%)[b]	**355a** yield (%)[b]	acid **361** (%)[b]
1	no	no	-	-	25
2	no	yes	-	-	29
3	yes	no	-	-	84

[a] Reaction conditions: 2-phenylpyridine (1.0 mmol), *ortho*-toluoyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields.

As the base plays an important role in the acylation reaction, it was decided to investigate the effect that the stoichiometry of K_2CO_3 has on C-H the acylation of 2-phenylpyridine (Table 27). With 2 equivalents of K_2CO_3, the yield obtained was 38% (Table 27, entry 1) and increasing it to 3 and 4 equivalents provided the *ortho*-acylated product in 49% and 52% respectively (Table 27, entries 2 & 3). Upon increasing the amount of base to more than 5 equivalents, the yield started to decrease and gave 49% of the *ortho*-acylated product (Table 27, entry 5). From this observation, the optimum threshold for base to employ in the reaction is 5 equivalents of K_2CO_3, in addition it is noteworthy that the current optimised conditions are more efficient than Kakiuchi's acylation conditions as they obtained 56% of **355a** and also no diacylated products were formed under our acylation conditions.

Table 27. Effects of K_2CO_3 stoichiometry on ruthenium-catalysed C-H acylation of 2-phenylpyridine



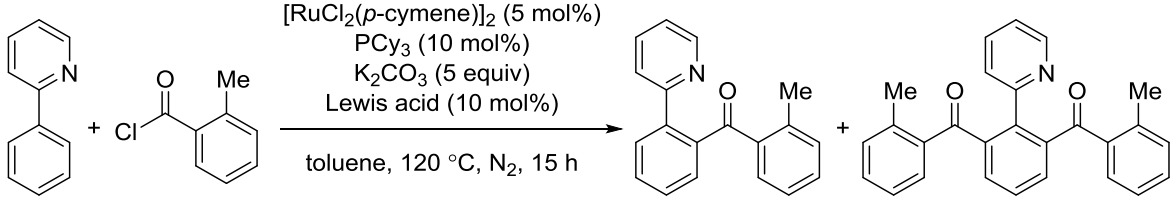
63 **354** (2.5 equiv) **360** **355a** (lit: 56%)

entry[a]	No. of equivalence of K_2CO_3	**360** yield (%)[b]	**355a** yield (%)[b]
1	2	-	38
2	3	-	49
3	4	-	52
4	**5**	**-**	**61**
5	6	-	49

[a] Reaction conditions: 2-phenylpyridine (1.0 mmol), *ortho*-toluoyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (x equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields.

As Lewis acids are known to activate acid chlorides, selected Lewis acids were screened next in the catalytic process (Table 28). There was no clear correlation with the addition of Lewis acids in the reaction. $Ag(OTf)_2$ and $InCl_3$ gave poor yields (Table 28, entries 2 & 3) and $Zn(OTf)_3$ gave a moderate yield of 39% of the *ortho*-acylated product (Table 28, entry 4). On the other hand, $In(OTf)_3$ and $Ti(O^iPr)_4$ failed to yield any products (Table 28, entry 5 & 6). The use of $CuCl_2$ gave satisfactory yields and promoted the reaction as both the mono and bisacylated products **355a** and **355b** were afforded in the reaction (Table 28, entry 1), which was not observed under previous conditions during the optimisation study. Although some of the Lewis acids examined were effective in the reaction, unfortunately, none of the Lewis acids screened served to increase the yield.

Table 28. Effects of addition of Lewis acids on ruthenium-catalysed C-H acylation of 2-phenylpyridine



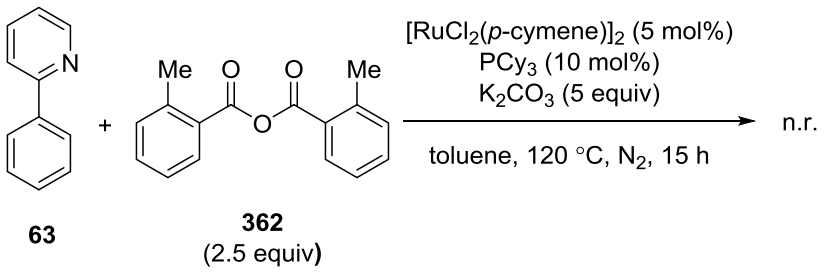
63 **354** (2.5 equiv) **355a** (lit: 56%) **355b** (lit: 5%)

entry[a]	Lewis acid	**355a** yield (%)[b]	**355b** yield (%)[b]
1	$CuCl_2$	48	7
2	$Ag(OTf)_2$	15	-
3	$InCl_3$	11	-
4	$Zn(OTf)_2$	39	-
5	$In(OTf)_3$	-	-
6	$Ti(O^iPr)_4$	-	-

[a] Reaction conditions: 2-phenylpyridine (1.0 mmol), *ortho*-toluoyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), Lewis acid (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields.

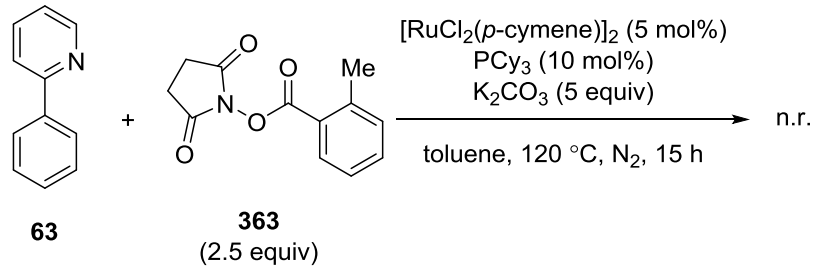
It is noteworthy, that the acid chlorides decomposed over time, so it has to be distilled prior to use in the reaction, this was the case for *ortho*-toluoyl chloride and it was distilled and dried over 3 Å molecular sieves.

The next step was to investigate if there were any other forms of *ortho*-toluoyl chloride that can be used as an acylating reagent for the C-H acylation. The anhydride 2-methylbenzoic anhydride **362** was synthesised, and treated the anhydride **362** under the C-H acylation conditions, however, after 15 hours of heating, no products were formed in the reaction (Scheme 142).



Scheme 142

The succinimide version **363** was also synthesised, but unfortunately, it was also unreactive, in this regard, anhydrides can be eliminated as a potential electrophile in the present ruthenium-catalysed acylation (Scheme 143).

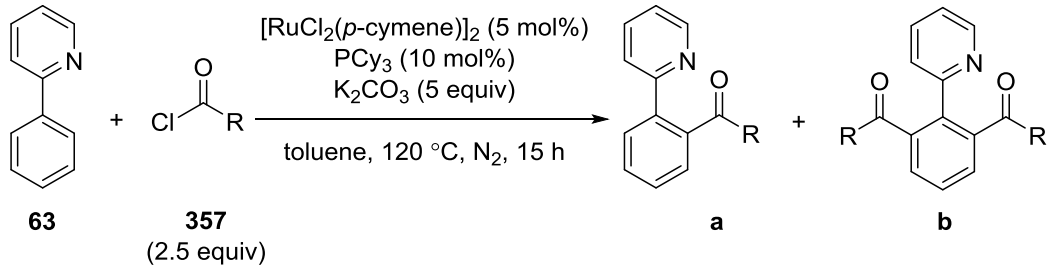


Scheme 143

With the optimised conditions in hand, the scope of the acylation of 2-phenylpyridine was examined (Table 29). *Ortho*-substituted aryl acid chlorides such as 2-methoxybenzoyl and 2-trifluoromethylbenzoyl chloride were treated under the acylation conditions, and surprisingly, both acid chlorides were unreactive (Table 29, entries 2 & 3). It is not clear why this is the case, since *ortho*-toluoyl chloride is a compatible coupling partner, the results could be due to electronic or steric reasons. In terms of steric hindrance, the OMe and CF_3 groups are only slightly larger than the CH_3 group, considering this; these groups should not inhibit the reaction. In terms of electronic effects, OMe, CF_3 and CH_3 are all electronically different. In general, the electron deficient electrophile should be reactive towards oxidative addition in the presence of a nucleophilic metal complex; however, it is not the case, under our acylation conditions.[45] In this regard, it seems that utilising an aryl acid chloride containing either a strongly electron-donating or an electron-withdrawing group reduces its reactivity towards *ortho* C-H acylation. Other aryl acid chlorides such as 4-methoxybenzoyl and 2-naphthyl chloride were also unreactive (Table 29, entries 4 & 5), in contrast the sterically hindered 2,4,6-trimethylbenzoyl chloride gave the

corresponding acylated product **364** in 25% yield (Table 29, entry 6). Unfortunately, alkyl acid chlorides such as cyclopropanecarbonyl chloride and trimethylacetyl chloride were also unreactive (Table 29, entries 7 & 8). From table 29, it clearly shows that this reaction has limited scope with 2-phenylpyridine and only two of the aryl acid chlorides tested were compatible as coupling partners.

Table 29. Scope of ruthenium-catalysed C-H acylation of 2-phenylpyridine



entry[a]	R	product	**a** yield (%)[b]	**b** yield (%)[b]
1	2-MeC_6H_4	**355**	61	-
2	2-$OMeC_6H_4$	-	-	-
3	2-$CF_3C_6H_4$	-	-	-
4	4-$OMeC_6H_4$	-	-	-
5	2-naphthyl	-	-	-
6	Mes	**364**	25	-
7	cyclopropane	-	-	-
8	^{t}Bu	-	-	-

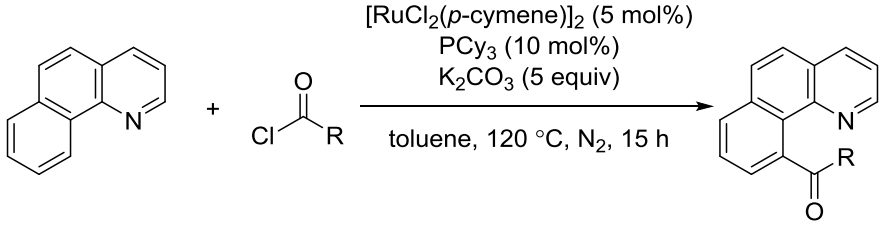
[a] Reaction conditions: 2-phenylpyridine (1.0 mmol), acid chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields.

With the disappointing results with 2-phenylpyridine, it was decided to search for other directing groups to perform the C-H acylation reaction. 2-Phenylquinoline and 2-phenyl-2-oxazoline were not compatible under the acylation conditions as for the latter, the crude ^{1}H NMR spectrum indicated the ring-opened product was being formed, *via* ring-opening of oxazoline in the presence of an acid chloride which is well documented in the literature.[46]

3.3.1b. Ru(II)-catalysed C-H acylation of benzo[*h*]quinoline

The next substrate examined was benzo[*h*]quinoline because this substrate has also been employed in C-H acylations as reported by Kakiuchi. Benzo[*h*]quinoline was treated with various acid chlorides under the optimised acylation conditions (Table 30). Coupling of benzoyl and *ortho*-toluoyl chloride under the optimised conditions provided the *ortho*-acylated products **358a** and **358b** in moderate yields of 10 and 34% respectively (Table 30, entries 1 & 2), however the yields are comparatively lower than the yields reported by Kakiuchi. Because of the low yields obtained with the aryl acid chlorides, it was decided to attempt the reaction with alkyl acid chlorides as coupling partners. Reaction of benzo[*h*]quinoline with cyclopropanecarbonyl chloride and trimethylacetyl chloride gave the corresponding products **358g** and **358h** in 34 and 9% respectively (Table 30, entries 3 & 4). It is noteworthy that other than the methodology presented herein, the only other strategy to produce *ortho* aliphatic acylated benzo[*h*]quinoline is reported by Li's group that employs a palladium catalyst and aldehydes as the electrophile.[15]

Table 30. Scope of ruthenium-catalysed C-H acylation of benzo[*h*]quinoline



250 **357** (2.5 equiv) **358**

entry[a]	R	product	yield (%)[b]
1	Ph	**358a**	10 (95)[c]
2	2-MeC_6H_4[d]	**358b**	34 (84)[c]
3	cyclopropane[d]	**358g**	34
4	^{t}Bu	**358h**	9

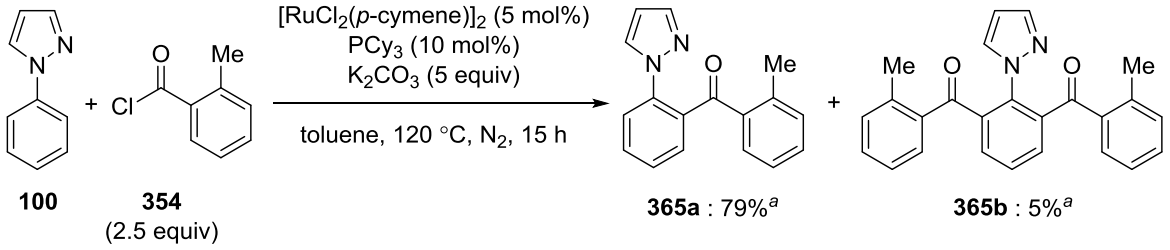
[a] Reaction conditions: benzo[*h*]quinoline (1.0 mmol), acid chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields. [c] Literature yield reported by Kakiuchi in parentheses. [d] Acid chloride was distilled and dried over 3 Å molecular sieves.

At this point, it was felt that the yields obtained so far were disappointingly low for C-H acylation of benzo[*h*]quinoline, so it was decided to discontinue this investigation and pursue a different directing group instead.

3.3.1c. Ruthenium-catalysed C-H acylation of 1-phenylpyrazole[47]

As mentioned previously in chapter 2, 1-phenylpyrazole was able to undergo *meta*-C-H sulfonation albeit in a low yield. At present, there are only a few methods of C-H acylation of phenylpyrazoles documented in the literature. One method is the Ru(0)-catalysed C-H carbonylation developed by Murai and another strategy employs a palladium catalyst and benzyl ether as the acyl equivalent.[13, 48]

Therefore, it was decided to attempt to employ 1-phenylpyrazole **100** as the substrate for C-H acylation. Treatment of 1-phenylpyrazole with *ortho*-toluoyl chloride **354** under the acylation conditions provided the monoacylated **365a** and bisacylated **365b** phenylpyrazoles in 79% and 5% conversion respectively (Scheme 144). Separation of the two products was attempted by flash column chromatography, unfortunately the products were unable to be purified because of the similar R_f values of the two products. Despite that, the acylated products were isolated as a mixture, nevertheless this was a promising result, as this was the first example of C-H acylation of 1-phenylpyrazole utilising acid chlorides as the acylating reagent.

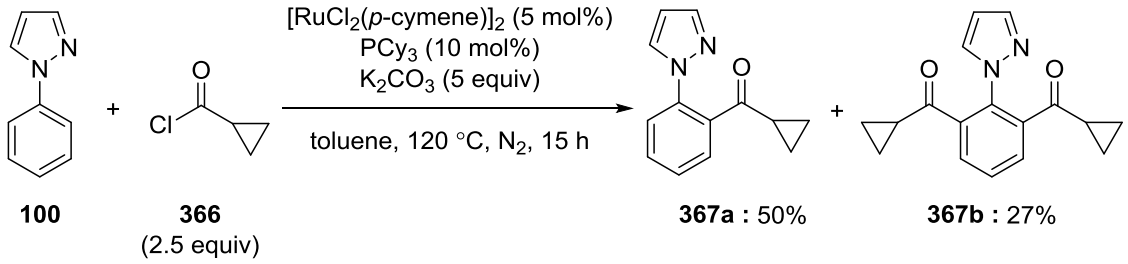


100 **354** (2.5 equiv) **365a** : 79%[a] **365b** : 5%[a]

Scheme 146. [a] ^{1}H NMR conversions

To ensure the reaction is not limited to aryl acid chlorides, it was decided to attempt the reaction with an alkyl acid chloride. Acylation of 1-phenylpyrazole was performed with cyclopropanecarbonyl chloride **366** as it was a compatible coupling partner for acylation of benzo[*h*]quinoline. Acylation of 1-phenylpyrazole **100** with cyclopropanecarbonyl chloride **366**

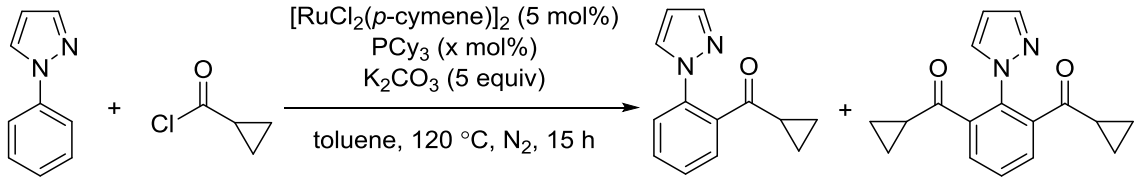
proceeded smoothly and afforded both the mono **367a** and bisacylated **367b** products cleanly in 50% and 27% isolated yield respectively (Scheme 145).



Scheme 145

Although the conversion for the *ortho*-acylation of 1-phenylpyrazole was high, it was decided to attempt to further optimise the C-H acylation of 1-phenylpyrazole using cyclopropanecarbonyl chloride as the coupling partner. The variable examined was the amount of PCy_3 ligand added into the reaction (Table 31). In the absence of the phosphine ligand, there was no reaction (Table 31, entry 1), from this finding, it can be implied that PCy_3 is required for the acylation of phenylpyrazole to proceed. With 5 mol% of PCy_3, it gave the bisacylated product as the major product in 75% yield (Table 31, entry 2). It seems that when the ligand loading is above 10 mol%, the yield starts to drop as observed in the table, with 15 mol% the yield for the monoacylated product decreases to 36% (Table 31, entry 4), yet the yield for diacylation remains unaffected. Contrastingly, in the presence of 20 mol% of PCy_3, only a trace amount of the bisacylated product is detected and the monoacylated product is made as the major product in 42% yield (Table 31, entry, 5). As for addition of 30 mol% of ligand, no products were formed at all (Table 31, entry 6). From table 31 it clearly shows that the selectivity to obtain either the mono or bisacylated product as the major product can be controlled by the amount of PCy_3 added to the reaction.

Table 31. Effects of PCy_3 loading on ruthenium-catalysed C-H acylation of 1-phenylpyrazole



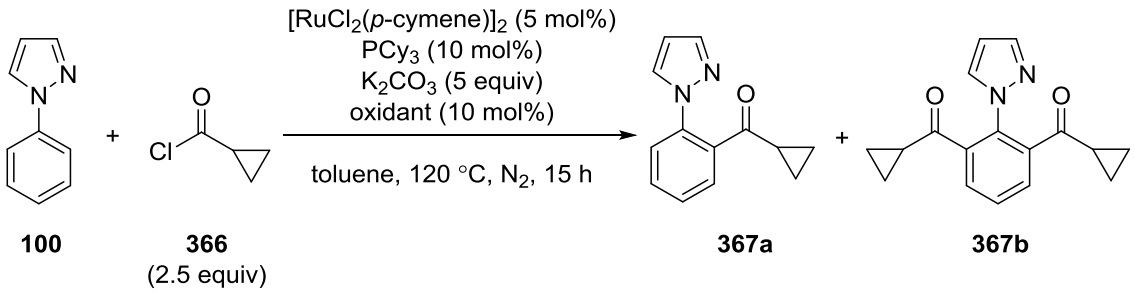
100 **366** (2.5 equiv) **367a** **367b**

entry[a]	PCy_3 (mol%)	**367a** yield (%)[b]	**367b** yield (%)[b]
1	-	-	-
2	5	15	75
3	**10**	**50**	**27**
4	15	36	29
5	20	42	trace
6	30	-	-

[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), cyclopropanecarbonyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (x mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. Cyclopropanecarbonyl chloride was distilled and dried over 3 Å molecular sieves. [b] Isolated yields.

Further optimisation was attempted with the use of oxidants, as the presence of oxidant could facilitate the regeneration of the active catalyst species (Table 32). Reaction under aerobic conditions was undesirable as no products were formed (Table 32, entry 3). In contrast, oxidants such as $FeCl_3$ gave a high overall yield of 89%, but it is worth noting that the ratio of the two products is 1.3:1 (Table 32, entry 1). This ratio is not ideal, because under these conditions there is no selectivity between the mono **367a** and bisacylated **367b** products. On the other hand, reaction with the addition of $Cu(OAc)_2$ provided only the monoacylation product **367a** in 45% yield (Table 32, entry 2).

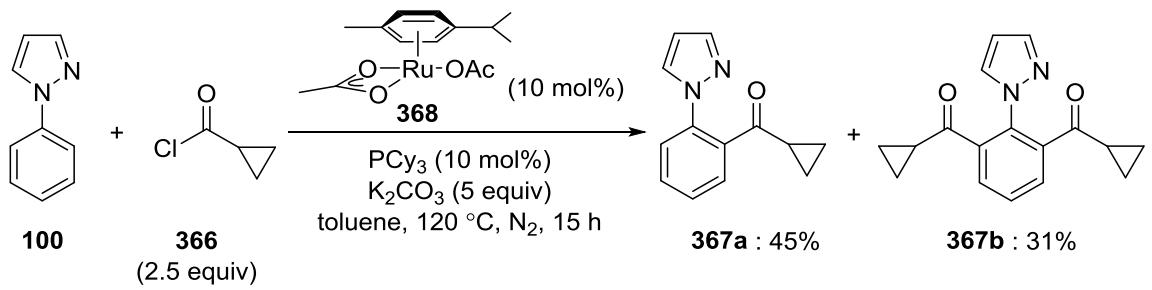
Table 32. Effects of addition of oxidant in the ruthenium-catalysed C-H acylation of 1-phenylpyrazole



entry[a]	oxidant	**367a** yield (%)[b]	**367b** yield (%)[b]
1	$FeCl_3$	50	39
2	$Cu(OAc)_2$	45	-
3	O_2	-	-

[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), cyclopropanecarbonyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), oxidant (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. Cyclopropanecarbonyl chloride was distilled and dried over 3 Å molecular sieves. [b] Isolated yields.

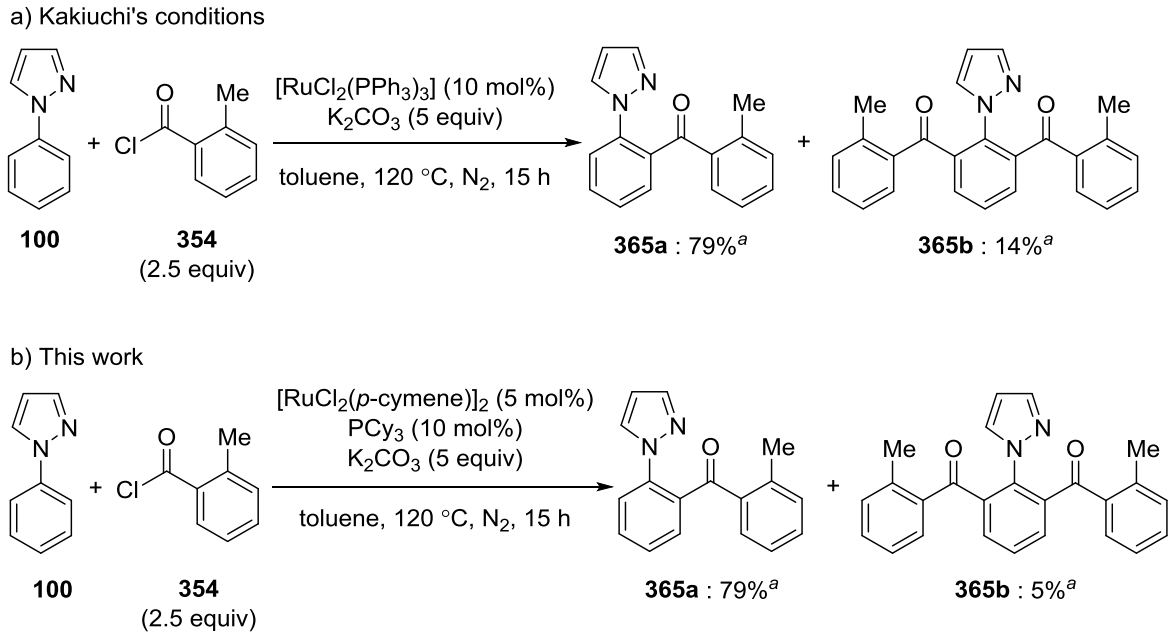
The ruthenium complex, $[Ru(OAc)_2(p\text{-cymene})]$ **368** was synthesised as reported by Stephenson *et al.* and employed **368** as the catalyst,[49] because this catalyst has shown to have high catalytic efficiency in various C-H functionalisation reactions.[50, 51] For this reason, acylation was performed in the presence of 10 mol% of $[Ru(OAc)_2(p\text{-cymene})]$ and gave the mono **367a** and bisacylated **367b** products in 45% and 31% respectively, compared to the present conditions, the yields are comparable (Scheme 146).



Scheme 146

From this further optimisation study, the changes made to the standard conditions did not further improved the yield, so it was decided to employ the standard conditions for the scope of C-H acylation of phenylpyrazole.

Before exploring the reaction scope, it was of interest to investigate whether or not Kakiuchi's acylation conditions would also be applicable to 1-phenylpyrazole, as it was not reported in their study. Kakiuchi's conditions was employed for the acylation of 1-phenylpyrazole **100** with *ortho*-toluoyl chloride **354**. The conversions obtained under Kakiuchi's conditions are somewhat similar to the present work, except that the diacylated product **365b** was obtained in a higher conversion of 14%, making Kakiuchi's less selective than the present reaction conditions (Scheme 147).[40]



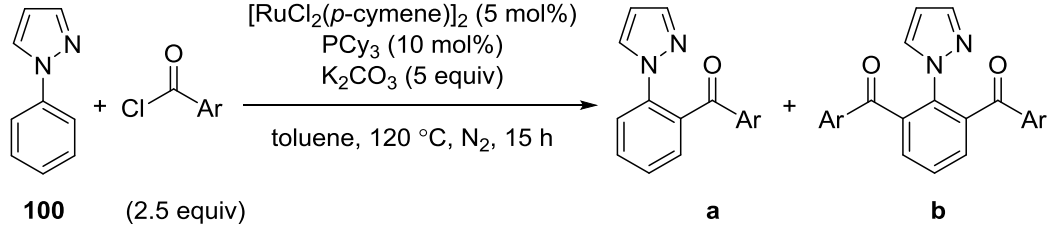
Scheme 147 *a* ^{1}H NMR conversions

As the C-H acylation of 1-phenylpyrazole with acid chlorides has not been reported in the literature previously, it was decided to continue to investigate and explore the scope of the ruthenium(II) catalysed C-H acylation of 1-phenylpyrazole (Table 33).

Firstly, aryl acid chlorides were subjected to the acylation conditions. Benzoyl and 2,4,6-trimethylbenzoyl chloride gave low conversions (Table 33, entries 3 and 4). Similar to 2-phenylpyridine, 2-methoxybenzoyl chloride and 2-trifluoromethylbenzoyl chloride were unreactive under the standard conditions (Table 33, entries 5 & 6). Contrastingly, 2-bromobenzoyl chloride afforded the *ortho*-acylated product **369** cleanly in 29% yield (Table 33, entry 2), with the bromine functional handle, further functionalisations could be performed. Other aryl acid

chlorides were investigated in the reaction. Electron-donating and electron-withdrawing groups on the aryl acid chloride, such as OMe and NO_2 groups are not tolerated in the reaction. Additionally, heteroaromatic acid chlorides failed to react. These results agree with the findings observed in the acylation of 2-phenylpyridine with aryl acid chlorides, where aryl acid chlorides containing strong electron-donating or electron-withdrawing groups inhibits the reactivity of the acid chloride towards C-H acylation. However, methyl or bromine substituted aryl acid chlorides are compatible coupling partners. This suggests only a substituent that releases or withdraws electrons *via* the inductive effect are compatible, as a methyl group is an inductively donating group and bromine is an inductively withdrawing group. It is noteworthy that halogens are also electron-donating *via* conjugation of its lone pairs to the aromatic ring, however because of its electronegative character and the mismatch in orbital size with the carbon atoms there is poor orbital overlap. Therefore, the halogen's major influence is based on inductive effects. With the limited scope, it was decided to explore the alkyl acid chlorides as coupling partners.

Table 33. Scope of ruthenium-catalysed C-H acylation of 1-phenylpyrazole with aryl acid chlorides

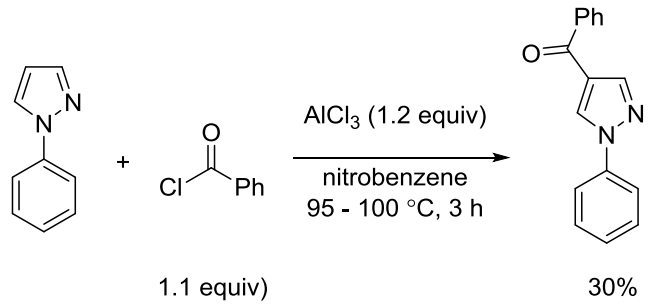


100 (2.5 equiv) **a** **b**

entry[a]	Ar	product	a yield (%)[b]	b yield (%)[b]
1	2-MeC_6H_4	**365**	79[c]	5[c]
2	2-BrC_6H_4	**369**	29	-
3	Ph	**370**	24[d]	-
4	Mes	**371**	3[c]	8[c]
5	2-$OMeC_6H_4$	-	-	-
6	2-$CF_3C_6H_4$		-	-
7	4-$OMeC_6H_4$	-	-	-
8	4-$NO_2C_6H_4$	-	-	-
9	3,5-$NO_2C_6H_3$	-	-	-
10	2-thiophene	-	-	-
11	2-furoyl	-	-	-

[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), acid chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. *ortho*-Toluoyl chloride was distilled and dried over 3 Å molecular sieves. [b] Isolated yield. [c] Isolated as a mixture of mono and diacylated products. [d] Isolated as an inseparable mixture with the phenylpyrazole dimer.

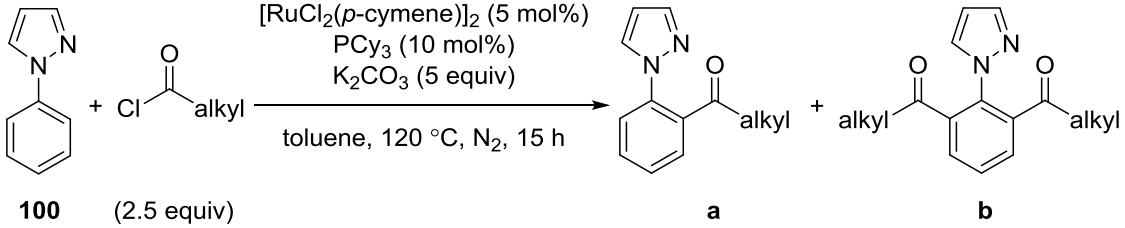
A range of aliphatic acid chlorides were reacted under the standard acylation conditions to provide aliphatic acyl groups on phenylpyrazole (Table 34). Reaction with acetyl chloride gave the corresponding product **372** in 28% yield; however, by performing the reaction on a larger scale a higher yield of 41% was achieved (Table 34, entry 1). This is the first example of **372** being prepared *via* catalytic C-H functionalisation and it provides further evidence that the reaction is not *via* the classic Friedel-Crafts pathway. As acylation *via* the classic Friedel-Crafts reaction, the acid chloride is substituted on the 4-position of the pyrazole ring (Scheme 148).[52]



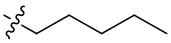
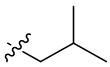
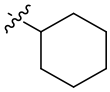
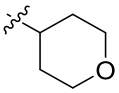
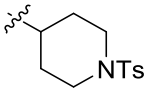
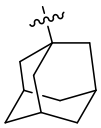
Scheme 148

For acyclic and cyclic alkyl acid chlorides there is a notable correlation in which higher yields of acylation products obtained for the more sterically hindered acid chlorides. One example is when trimethylacetyl chloride and adamantanecarbonyl chloride were used as electrophile (Table 34, entries 6 and 13). Another example is the increasing size of the cyclic alkyl acid chloride, with cyclopropanecarbonyl chloride, the high ring strain, provided an overall yield of 77% of the two products **367a** and **367b** (Table 34, entry 7). In contrast, cyclobutanecarbonyl chloride gave no products, even though the reaction was performed in a sealed vial because of the low boiling point of the acid chloride, still no acylation products were observed. On the other hand, cyclopentane and cyclohexanecarbonyl chloride provided low yields of 6% and 28% respectively (Table 34, entries 9 and 10). However, tetrahydropyran carbonyl chloride and 1-tosylpiperidine carbonyl chloride were less reactive than the cyclohexanecarbonyl chloride (Table 34, entries 11 & 12). It is unknown for the reactivity observed between the various cyclic alkyl acid chlorides, it can be postulated that due to the high reaction temperature the cyclobutanecarbonyl chloride can interchange between the planar and puckered conformer, it causes more steric interactions which could hinder the oxidative addition step. *Iso*butyryl chloride afforded the *ortho*-acylated product **375a** in 56% yield (Table 34, entry 4), and in comparison the dichloroacetyl chloride was unreactive (Table 34, entry 5). From Table 34, the higher yields obtained for the sterically hindered acid chlorides suggest that this C-H acylation of phenylpyrazole is most likely due to steric acceleration during the reductive elimination step, hence the high preference for sterically hindered acid chlorides.[53-55]

Table 34. Scope of ruthenium-catalysed C-H acylation of 1-phenylpyrazole with aryl acid chlorides



100 (2.5 equiv) **a** **b**

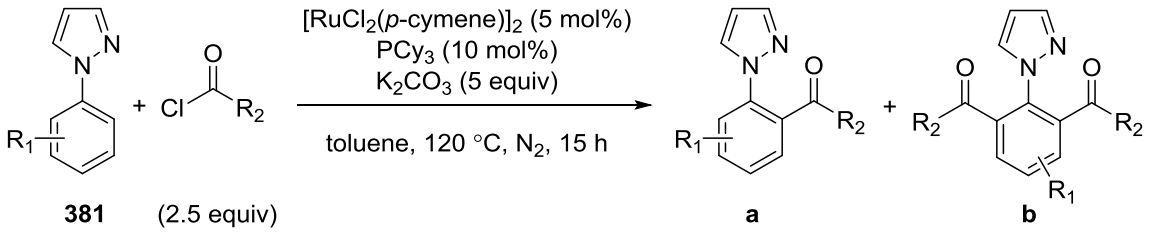
entry[a]	alkyl	product	**a** yield (%)[b]	**b** yield (%)[b]
1	Me	**372**	28[c] (41[d])	-
2		**373**	7	-
3		**374**	30	-
4		**375**	56	-
5		**-**	-	-
6		**376**	53	-
7		**367**	50	27
8		**-**	-	-
9		**377**	6	-
10		**378**	28	-
11		**379**	10	-
12		**-**	-	-
13		**380**	76	-

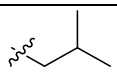
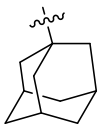
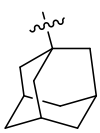
[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), acid chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. Cyclopropanecarbonyl chloride, cyclopentanecarbonyl chloride, cyclohexanecarbonyl chloride and *o*-toluoyl chloride were distilled and

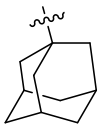
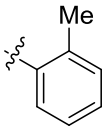
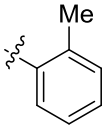
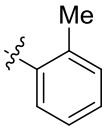
dried over 3 Å molecular sieves. [b] Isolated yield. [c] Reaction performed in a sealed vial. [d] On a 5 mmol scale, in a sealed Schlenk tube.

To further evaluate the scope of this reaction a range of 1-arylpyrazole derivatives were synthesised under the conditions reported by Bolm and coupled with various acid chlorides under identical conditions (Table 35).[56] The electronic properties of the substituent significantly affected the feasibility of the reaction. The reaction was promoted by electron donating groups and retarded by electron-withdrawing substituents. The selectivity of catalytic mono- and diacylation appears to be influenced by steric hinderance on the aryl ring. For the majority of the examples shown in Table 35, only the monoacylated products were obtained. In particular, the electron-rich *meta*-substituted substrates in combination with sterically hindered acyl chlorides afforded products in high yields (Table 35, entries 7 and 8). Interestingly, exchanging the *meta* Me to a CF_3 group switched off the reactivity, despite the fact that the latter substrate has a high chance to undergo cyclometallation. In addition, other substituents such as fluoro and methyl ketone are not compatible in the reaction. It appears that the reaction is sensitive to substituent effects, and the introduction of any electron-withdrawing substituents seems to have a detrimental effect on the reactivity. On the other hand, 4-OMe substituted substrate **381k** was unreactive. 1-Phenylindazole **381e** was also found to be a suitable substrate for catalytic C-H acylation and afforded the corresponding acylated product **390** in 45% yield (Table 35, entry 9), which is comparable to **376**.

Table 35. Scope of ruthenium-catalysed C-H acylation of phenylprazole derivatives with aryl and alkyl acid chlorides



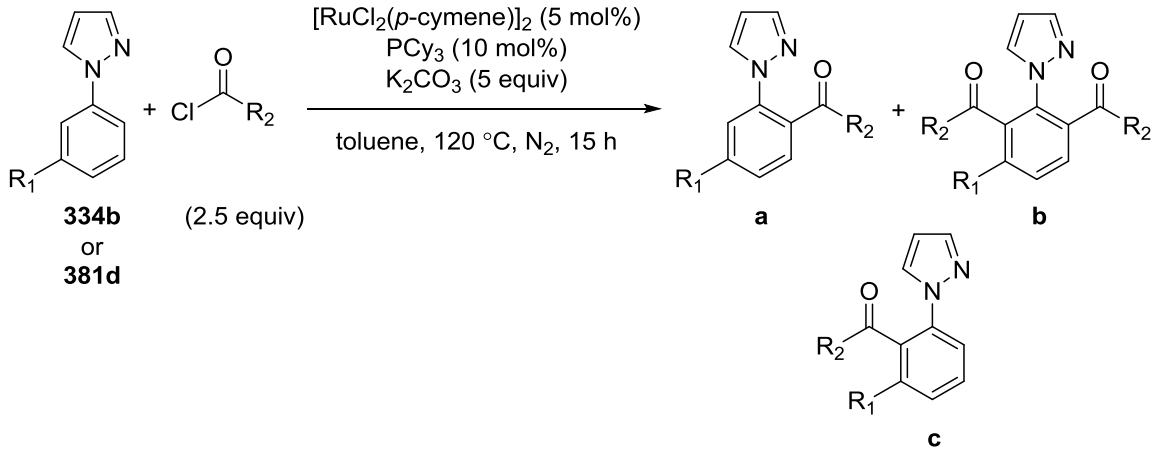
entry[a]	R_1	R_2	product	**a** yield (%)[b]	**b** yield (%)[b]
1	4-Me (**334a**)		**382**	22	-
2	4-Me (**334a**)		**383**	60	-
3	4-Me (**334a**)		**384**	28	12
4	4-Et (**381a**)		**385**	67	-
5	4-Ph (**381b**)		**386**	11	-
6	4-^{t}Bu (**381c**)		**387**	72	-
7	3-Me (**381d**)		**388**	91	-
8	3-OMe (**334b**)		**389**	92	-
9	H[c] (**381e**)		**390**	45	-
10	3-NH(CO)^{t}Bu (**381f**)		**391**	2	-
11	3-NMe_2 (**381g**)		**392**	4	-
12	3-Me (**381d**)		**393**	54	-
13	3-OMe (**334b**)		**394**	52	-

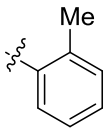
14	4-^{t}Bu (**381c**)		**395**	52	-
15	3-NH(CO)^{t}Bu (**381f**)		**396**	14	-
16	4-F (**381h**)		**-**	-	-
17	4-C(O)Me (**381i**)		**-**	-	-
18	3-CF_3 (**381j**)		**-**	-	-
19	4-OMe (**381k**)		**-**	-	-

[a] Reaction conditions: 1-phenylpyrazole derivative (1.0 mmol), acid chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. Cyclopropanecarbonyl chloride, cyclopentanecarbonyl chloride, cyclohexanecarbonyl chloride and *o*-toluoyl chloride were distilled and dried over 3 Å molecular sieves. [b] Isolated yields. [c] Indazole.

Interestingly, C-H acylation of 3-OMe **334b** with cyclopropanecarbonyl chloride resulted in the formation of three products (Table 36, entry 1). The major product was the *ortho* monoacylated product **397a** and this is based on steric arguments for the cyclometallation. The other *ortho*-acylated regioisomer **397c** was obtained in a low yield along with the diacylated product **397b**. The formation of the *ortho* regioisomer **397c** is most likely due to the electron-rich methoxy substituent, acting as a directing group to promote acylation *ortho/para* to the methoxy substituent. The lower yield for the *ortho*-acylated regioisomer **397c** can be attributed to the increased steric interaction between the C-3 substituent and the ruthenium fragment hindering cyclometallation in the *ortho* position. This reactivity was also observed when **334b** was reacted with *ortho*-toluoyl chloride, but obtained poor yields across the three products (Table 36, entry 2). In contrast, reaction of **381d** with cyclopropanecarbonyl chloride only formed the two *ortho*-acylated regioisomers **399a** and **399c** as an inseparable mixture (Table 36, entry 3).

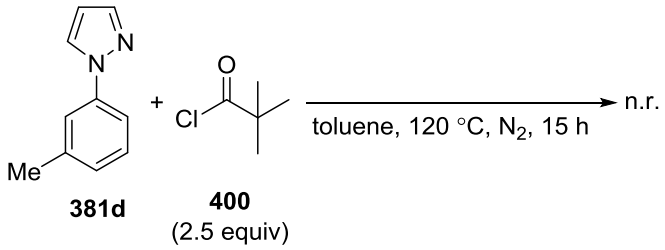
Table 36. Reaction of *meta*-methoxy and *meta*-methyl substituted phenylpyrazole with acid chlorides



entry[a]	R_1	R_2	product	**a** yield (%)[b]	**b** yield (%)[b]	**c** yield (%)[b]
1	3-OMe (**334b**)		**397**	51	13[c]	5
2	3-OMe (**334b**)		**398**	8	4	2
3	3-Me (**381d**)		**399**	28[d]	-	[d]

[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), acid chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. Cyclopropanecarbonyl chloride and *o*-toluoyl chloride were distilled and dried over 3 Å molecular sieves. [b] Isolated yields. [c] ^1H NMR conversion, as an inseparable mixture with the phenylpyrazole dimer. [d] As an inseparable mixture of regioisomers of **a** and **c**.

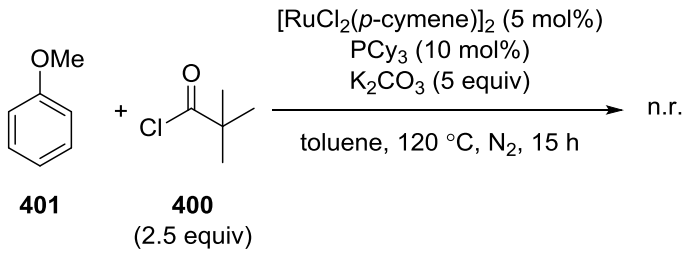
Because of the high reactivity observed with substrate **381d**, it was of interest to attempt the acylation reaction in the absence of catalyst and base to ensure that the high yield is the result of the catalytic process and not of other reasons. Reaction of substrate **381d** with trimethylacetyl chloride **400** gave no products and only the starting materials were recovered (Scheme 149). Thus, for C-H acylation to work, both the catalyst and base must be present in the reaction.



381d **400** (2.5 equiv)

Scheme 149

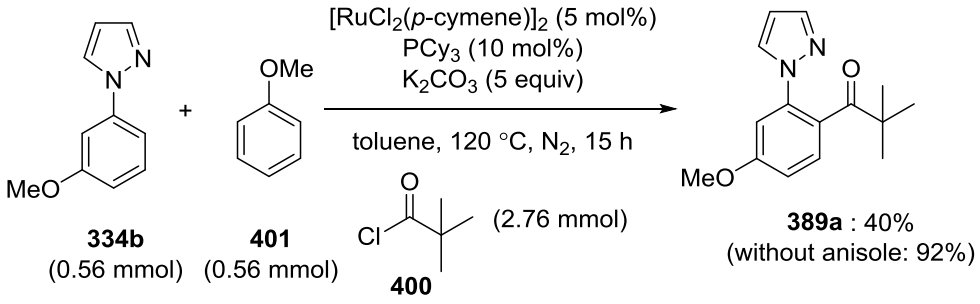
Other experiments were also performed to ensure the validity of the catalytic process. As mentioned in Table 35, substrate **334b** gave the acylated product **389a** in high yield, therefore to test if the methoxy group was acting as a directing group, which resulted in the high yield; anisole **401** was treated under the acylation conditions. After heating for 15 hours, no products were formed in the reaction (Scheme 150).



401 **400** (2.5 equiv)

Scheme 150

An intermolecular competition experiment between substrate **334b** and anisole **401** was performed under the C-H acylation conditions and found that the *ortho*-acylated product **389a** was made in 40% yield, which is a comparatively lower yield to that obtained in the absence of anisole (Scheme 151). This experiment suggests that anisole could be competing with phenylpyrazole for coordination to the ruthenium centre, hence the decrease in yield.

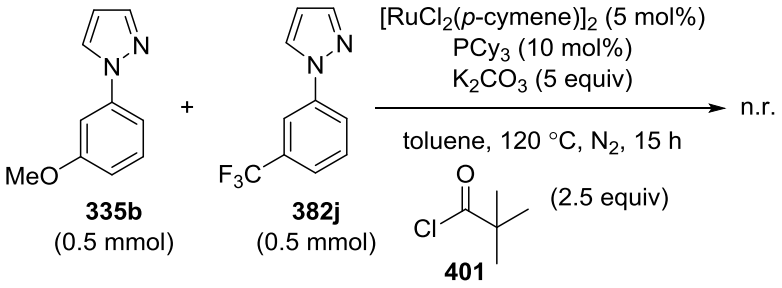


334b (0.56 mmol) **401** (0.56 mmol) **400**

389a : 40% (without anisole: 92%)

Scheme 151

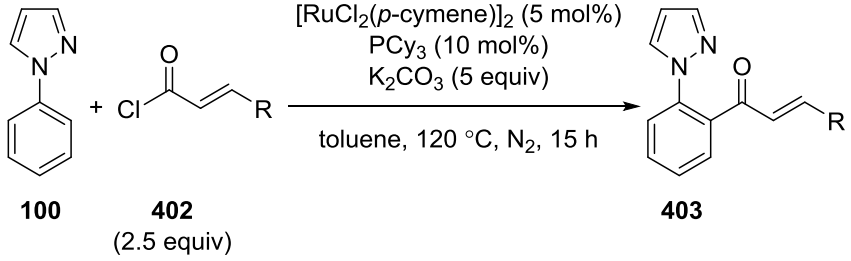
An intermolecular competition experiment was carried out between the *meta*-OMe substituent **334b** and the *meta*-CF_3 substituent **381j** under the standard acylation conditions (Scheme 152). Unfortunately, there was no reaction. From this result, it suggests that the *meta*-CF_3 substrate **381j** can cyclometallate as no products were formed in this reaction. In addition, it can proposed that the *meta*-CF_3 substrate **381j** cyclometallates at a faster rate than the *meta*-OMe substrate **334b**, as the electron-withdrawing CF_3 group withdraws electron density *para* to the substituent, it facilitates the cyclometallation process and all of the catalyst is consumed. Although the *meta*-CF_3 substrate **381j** can cyclometallate to form the ruthenacycle, it is unreactive as no products were formed in this competition reaction, or the reaction with trimethylacetyl chloride under the standard conditions (Table 35, entry 18).



Scheme 152

The next task was to explore other carbonyl chloride containing electrophiles. Alkenyl carbonylchloride such as acryloyl, crotonyl and cinnamoyl chlorides were employed as coupling partners under C-H acylation conditions to attempt to couple with 1-phenylpyrazole **100**. Disappointingly, no products were formed (Table 37). This may be ascribed to the electronic effects due to the presence of the double bond on the molecule, stabilising the carbonyl chloride and making it less reactive towards nucleophiles.

Table 37. Reactions of alkenyl carbonylchloride reacted with 1-phenylpyrazole under C-H acylation conditions

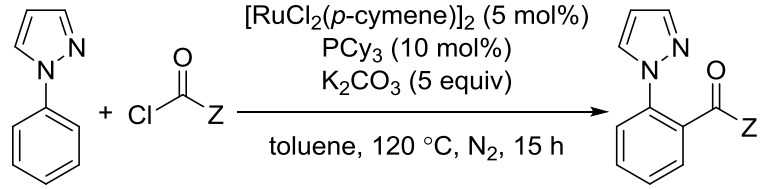


entry[a]	R	yield (%)
1	H	-
2	Me	-
3	Ph	-

[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), alkenylcarbonyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h.

It was then decided to attempt to use carbamoyl chlorides and chloroformates as acylating reagents as it has been reported in the literature that they promote direct amino- and alkoxycarbonylations *via* ruthenium catalysis.[39] Ethyl and *iso*butyl choroformates were efficiently coupled with 1-phenylpyrazole albeit in low yields, whereas phenyl chloroformate was unreactive. Dimethylcarbamoyl chloride gave the *ortho*-aminocarbonylated product **404c** in 10% yield. From Table 38, it appears that there was no catalytic turnover in the reaction, as none of the products were formed above 10% yield.

Table 38. Reactions of chloroformates or carbamoyl chlorides reacted with 1-phenylpyrazole under C-H acylation conditions



100 **350** (2.5 equiv) **404**

entry[a]	Z	product	yield (%)[b]
1	OEt	**404a**	9
2	$OCH_2CH(CH_3)_2$	**404b**	7
3	OPh	**-**	-
4	NMe_2	**404c**	10

[a] Reaction conditions: 1-phenylpyrazole (1.0 mmol), carbonyl chloride (2.5 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol%), PCy_3 (10 mol%), K_2CO_3 (5 equivalents), toluene (3 mL), 120 °C, N_2, 15 h. [b] Isolated yields.

3.3.2. Conclusions

In conclusion, ruthenium-catalysed C-H acylation of 2-phenylpyridine has been developed, utilising 5 mol% of $[RuCl_2(p\text{-cymene})]_2$, 10 mol% of PCy_3 and 5 equivalents of K_2CO_3 in toluene. The scope of C-H acylation of 2-phenylpyridine was found to be limited to only a couple of aryl acid chlorides. In contrast acylation of benzo[*h*]quinoline has a slightly broader scope, and it was shown that both aryl and alkyl acid chlorides were compatible coupling partners. However, C-H acylation of benzo[*h*]quinoline is less efficient compared to the study by Kakiuchi.

In the search for other directing groups to direct C-H acylation, it was discovered that phenylpyrazole derivatives were efficient chelating groups for the acylation. The reaction has a broad scope, in particular with alkyl acid chlorides in comparison to aryl acid chlorides, and the coupling of sterically hindered acid chlorides provided the best yields for the *ortho*-acylation. Interestingly, substrates containing either a *meta*-OMe or *meta*-Me substituent were very efficient substrates in this reaction, and it was hypothesised that the high reactivity of these substrates correlate to their respective Hammett constants. Other acylating reagents were

explored and it was found that carbamoyl chlorides and alkyl chloroformates were compatible coupling partners; however, catalytic turnover could not be achieved.

3.4. References

1. A. D. Ryabov, *Chem. Rev.*, 1990, **90**, 403-424.
2. A. R. Kapdi, *Dalton Trans.*, 2014, **43**, 3021-3034.
3. D. A. Colby, R. G. Bergman and J. A. Ellman, *Chem. Rev.*, 2010, **110**, 624-655.
4. T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**, 1147-1169.
5. P. B. Arockiam, C. Bruneau and P. H. Dixneuf, *Chem. Rev.*, 2012, **112**, 5879-5918.
6. C. D. Pan, X. F. Jia and J. Cheng, *Synthesis*, 2012, **44**, 677-685.
7. N. Chatani, T. Fukuyama, F. Kakiuchi and S. Murai, *J. Am. Chem. Soc.*, 1996, **118**, 493-494.
8. N. Chatani, Y. Ie, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 1997, **62**, 2604-2610.
9. N. Chatani, Y. Ishii, Y. Ie, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 1998, **63**, 5129-5136.
10. Y. Ie, N. Chatani, T. Ogo, D. R. Marshall, T. Fukuyama, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2000, **65**, 1475-1488.
11. N. Chatani, T. Fukuyama, H. Tatamidani, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2000, **65**, 4039-4047.
12. N. Chatani, S. Yorimitsu, T. Asaumi, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2002, **67**, 7557-7560.
13. T. Asaumi, N. Chatani, T. Matsuo, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2003, **68**, 7538-7540.
14. X. F. Jia, S. H. Zhang, W. H. Wang, F. Luo and J. Cheng, *Org. Lett.*, 2009, **11**, 3120-3123.
15. O. Basle, J. Bidange, Q. Shuai and C. J. Li, *Adv. Synth. Catal.*, 2010, **352**, 1145-1149.
16. B. X. Tang, R. J. Song, C. Y. Wu, Y. Liu, M. B. Zhou, W. T. Wei, G. B. Deng, D. L. Yin and J. H. Li, *J. Am. Chem. Soc.*, 2010, **132**, 8900-8902.
17. M. Z. Li and H. B. Ge, *Org. Lett.*, 2010, **12**, 3464-3467.
18. C. W. Chan, Z. Y. Zhou, A. S. C. Chan and W. Y. Yu, *Org. Lett.*, 2010, **12**, 3926-3929.
19. P. Alvarez-Bercedo, A. Flores-Gaspar, A. Correa and R. Martin, *J. Am. Chem. Soc.*, 2010, **132**, 466-467.
20. Y. N. Wu, B. Z. Li, F. Mao, X. S. Li and F. Y. Kwong, *Org. Lett.*, 2011, **13**, 3258-3261.
21. Y. Yuan, D. T. Chen and X. W. Wang, *Adv. Synth. Catal.*, 2011, **353**, 3373-3379.
22. F. H. Xiao, S. A. Qi, F. Zhao, O. Basle, G. J. Deng and C. J. Li, *Org. Lett.*, 2011, **13**, 1614-1617.
23. A. Flores-Gaspar, A. Gutierrez-Bonet and R. Martin, *Org. Lett.*, 2012, **14**, 5234-5237.
24. S. Guin, S. K. Rout, A. Banerjee, S. Nandi and B. K. Patel, *Org. Lett.*, 2012, **14**, 5294-5297.
25. Y. X. Yang, B. Zhou and Y. C. Li, *Adv. Synth. Catal.*, 2012, **354**, 2916-2920.
26. Z. W. Yin and P. P. Sun, *J. Org. Chem.*, 2012, **77**, 11339-11344.
27. B. Zhou, Y. X. Yang and Y. C. Li, *Chem. Commun.*, 2012, **48**, 5163-5165.
28. A. Banerjee, S. K. Santra, S. Guin, S. K. Rout and B. K. Patel, *Eur. J. Org. Chem.*, 2013, 1367-1376.
29. Q. P. Ding, H. F. Ji, C. Q. Ye, J. J. Wang, J. Y. Wang, L. Y. Zhou and Y. Y. Peng, *Tetrahedron*, 2013, **69**, 8661-8667.
30. M. Kim, S. Sharma, J. Park, M. Kim, Y. Choi, Y. Jeon, J. H. Kwak and I. S. Kim, *Tetrahedron*, 2013, **69**, 6552-6559.
31. J. Y. Lu, H. Zhang, X. W. Chen, H. X. Liu, Y. Y. Jiang and H. Fu, *Adv. Synth. Catal.*, 2013, **355**, 529-536.
32. S. Sharma, J. Park, E. Park, A. Kim, M. Kim, J. H. Kwak, Y. H. Jung and I. S. Kim, *Adv. Synth. Catal.*, 2013, **355**, 332-336.
33. Z. Z. Shi and F. Glorius, *Chem. Sci.*, 2013, **4**, 829-833.
34. F. Szabo, J. Daru, D. Simko, T. Z. Nagy, A. Stirling and Z. Novak, *Adv. Synth. Catal.*, 2013, **355**, 685-691.

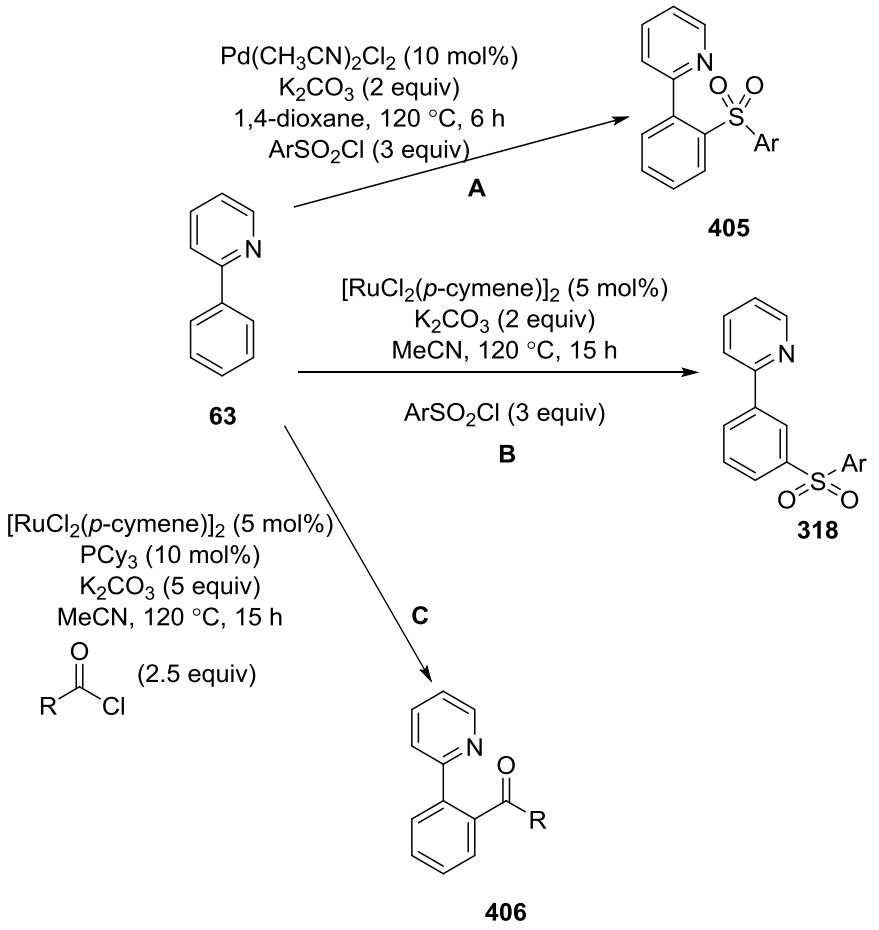
35. Y. N. Wu, P. Y. Choy, F. Mao and F. Y. Kwong, *Chem. Commun.*, 2013, **49**, 689-691.
36. Q. Zhang, F. Yang and Y. J. Wu, *Chem. Commun.*, 2013, **49**, 6837-6839.
37. H. Tang, C. Qian, D. E. Lin, H. F. Jiang and W. Zeng, *Adv. Synth. Catal.*, 2014, **356**, 519-527.
38. P. Mamone, G. Danoun and L. J. Goossen, *Angew. Chem. Int. Ed.*, 2013, **52**, 6704-6708.
39. T. Kochi, S. Urano, H. Seki, E. Mizushima, M. Sato and F. Kakiuchi, *J. Am. Chem. Soc.*, 2009, **131**, 2792-2793.
40. T. Kochi, A. Tazawa, K. Honda and F. Kakiuchi, *Chem. Lett.*, 2011, **40**, 1018-1020.
41. C. A. Tolman, *J. Am. Chem. Soc.*, 1970, **92**, 2953-2956.
42. C. A. Tolman, *J. Am. Chem. Soc.*, 1970, **92**, 2956-2965.
43. C. A. Tolman, *Chem. Rev.*, 1977, **77**, 313-348.
44. H. Clavier and S. P. Nolan, *Chem. Commun.*, 2010, **46**, 841-861.
45. R. Lerebours, A. Camacho-Soto and C. Wolf, *J. Org. Chem.*, 2005, **70**, 8601-8604.
46. T. G. Gant and A. I. Meyers, *Tetrahedron*, 1994, **50**, 2297-2360.
47. P. M. Liu and C. G. Frost, *Org. Lett.*, 2013, **15**, 5862-5865.
48. S. Han, S. Sharma, J. Park, M. Kim, Y. Shin, N. K. Mishra, J. J. Bae, J. H. Kwak, Y. H. Jung and I. S. Kim, *J. Org. Chem.*, 2014, **79**, 275-284.
49. D. A. Tocher, R. O. Gould, T. A. Stephenson, M. A. Bennett, J. P. Ennett, T. W. Matheson, L. Sawyer and V. K. Shah, *J. Chem. Soc. Dalton Trans.*, 1983, 1571-1581.
50. F. Pozgan and P. H. Dixneuf, *Adv. Synth. Catal.*, 2009, **351**, 1737-1743.
51. P. B. Arockiam, C. Fischmeister, C. Bruneau and P. H. Dixneuf, *Green Chem.*, 2011, **13**, 3075-3078.
52. I. L. Finar and T. Foster, *J. Chem. Soc. Org.*, 1967, 1494-1497.
53. B. C. Hamann and J. F. Hartwig, *J. Am. Chem. Soc.*, 1997, **119**, 12382-12383.
54. D. A. Culkin and J. F. Hartwig, *Organometallics*, 2004, **23**, 3398-3416.
55. J. F. Hartwig, *Inorg. Chem.*, 2007, **46**, 1936-1947.
56. A. Correa and C. Bolm, *Adv. Synth. Catal.*, 2007, **349**, 2673-2676.

Chapter 4. Mechanistic Insights Into Regioselectivity

4.1. Aims and Objectives

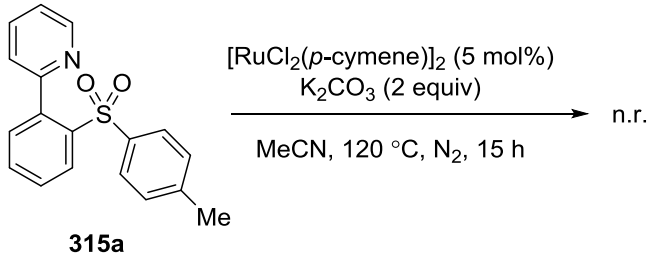
The goal in this chapter is to synthesise various ruthenium complexes and utilise these complexes in mechanistic experiments for understanding *meta*-C-H sulfonation and *ortho*-C-H acylation, and to explain how the two reactions provide products with different regioselectivity.

For the catalytic C-H sulfonation, the transition metal catalyst seems to have an influence on the regioselectivity of the product, as Dong and co-workers have described using $Pd(CH_3CN)_2Cl_2$ as the catalyst in the presence of K_2CO_3 for *ortho*-sulfonation of 2-phenylpyridine **63** in good yield (Scheme 153, route A). However, we have shown that by switching the catalyst from palladium to ruthenium, the regioselectivity of the product switches to the *meta*-position (Scheme 153, route B). In addition, when the sulfonyl chloride was replaced with an acid chloride as the electrophile, C-H acylation *via* ruthenium(II) catalysis gave the *ortho*-acylated product **406** (Scheme 153, route C). These results suggest diversions from a common mechanistic pathway. In this chapter, the individual steps and catalytic intermediates are investigated to enable an initial catalytic cycle to be presented.



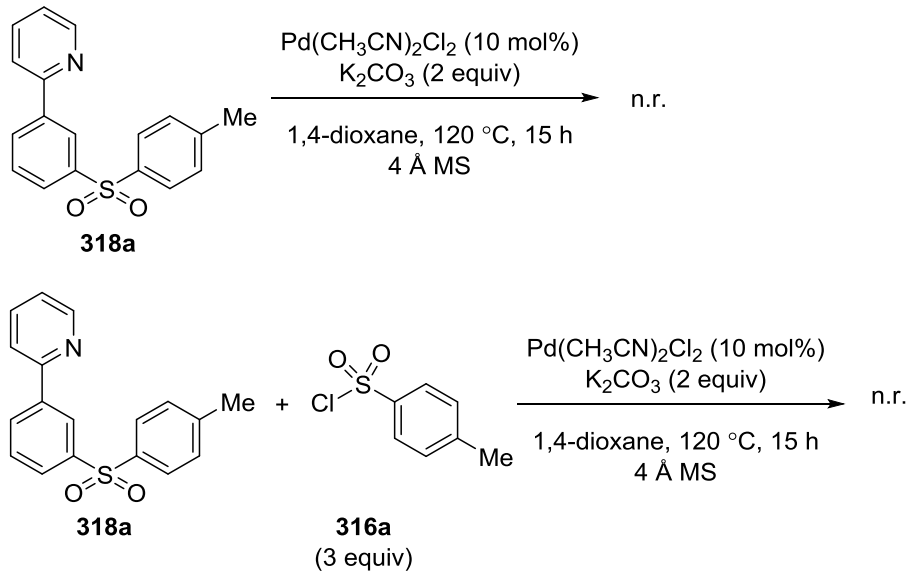
Scheme 153

For the *meta*-C-H sulfonation, one possible mechanism would be *via* the formation of the *ortho*-sulfone followed by a rearrangement to give the *meta*-sulfonated product. To test this hypothesis, the *ortho*-sulfone **315a** was synthesised following the procedure by Dong.[1] *Ortho*-sulfone **315a** was subjected under the *meta*-sulfonation conditions and no product was formed, this experimental finding shows that the *meta*-sulfonation is unlikely to be *via* a rearrangement of an *ortho*-sulfone (Scheme 154).



Scheme 154

Furthermore, the *meta*-sulfone **318a** was subjected under Dong's *ortho*-sulfonation conditions with or without the presence of *p*-TsCl **316a** in the reaction. In both cases, no product was formed in the reaction, and only the starting materials were recovered (Scheme 155). As no rearrangement was observed in these experiments, therefore this indicates our *meta*-C-H sulfonation must follow an alternative mechanistic pathway.

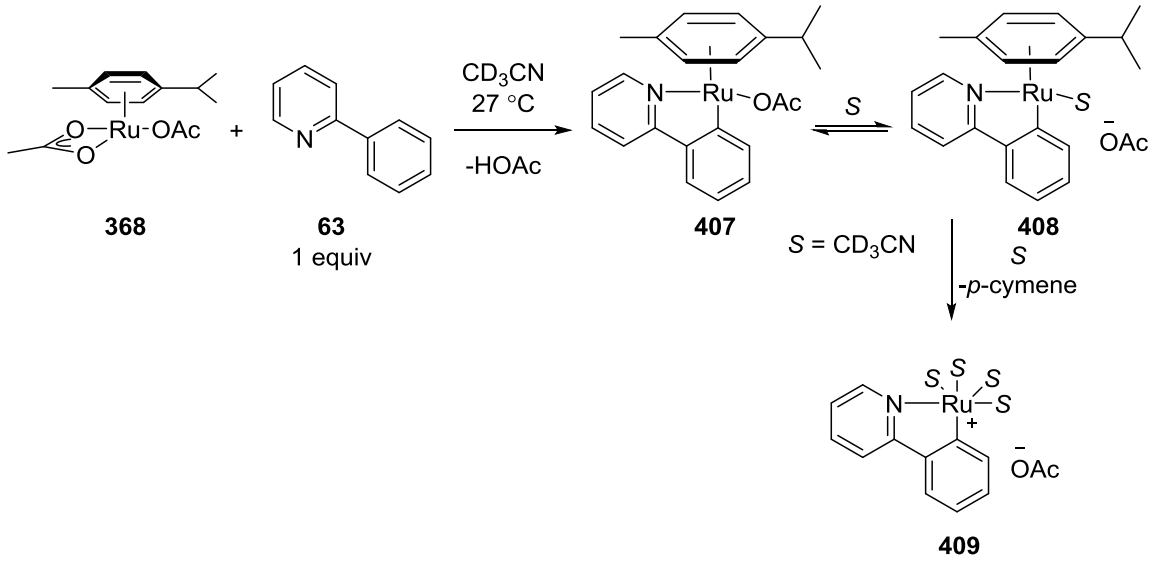


Scheme 155

4.1a. C-H activation process

To account for the different regioselectivity observed for the *meta*-sulfonation and *ortho*-acylation, it was decided to synthesise various ruthenium complexes to be used in stoichiometric experiments for understanding the mechanism of these two reactions. The first step of the mechanism is the C-H activation of the substrate. In 2011, Dixneuf and co-workers have reported studies on the autocatalytic processes of C-H activation by ruthenium complexes with various heteroarenes, including 2-phenylpyridine and 1-phenylpyrazole, which we have also explored under our *meta*-sulfonation and *ortho*-acylation conditions.[2, 3] In their study, it was found that during the C-H activation process of the chelating substrate with [$Ru(OAc)_2$(*p*-cymene)] at 27 °C, various ruthenium complexes were formed in the reaction. 2-Phenylpyridine **63** undergo C-H activation with complex **368** to cyclometallate to give complex **407**, which loses an acetate ligand in a reversible reaction to form complex **408**, and as time progresses, it loses the *p*-cymene ligand

to give complex **409** (Scheme 156). It is worth noting that complex **409** was only detected after 4 hours (detected **409** after 266 minutes) into the reaction.



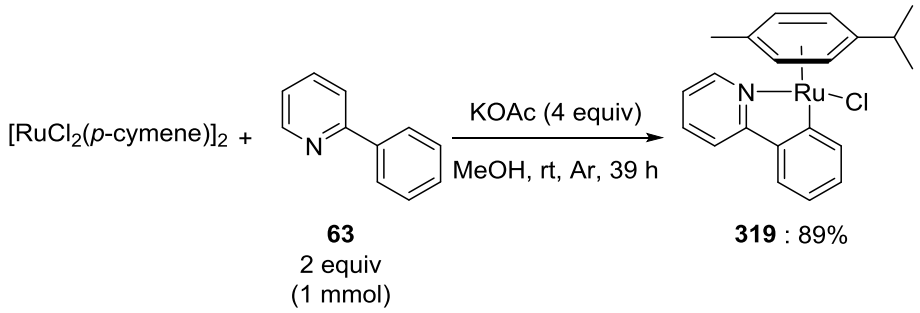
368 **63** 1 equiv **407** **408** **409**

Scheme 156

Since both Dixneuf's work and the work presented in this thesis use similar ruthenium(II) catalyst for the C-H bond transformations, it was hypothesised that the ruthenium-catalysed *meta*-C-H sulfonation and *ortho*-C-H acylation, are likely to undergo a similar mechanism for the C-H activation step. Dixneuf has reported synthesising each of the complexes individually by using $[RuCl_2(p\text{-cymene})]_2$ as the starting material, and it was decided to synthesise complexes of **407**, **408** and **409** as well as the ruthenium-substrate complex derivatives of phenylpyrazole and benzo[*h*]quinoline so that these complexes can be used in stoichiometric experiments for understanding the mechanisms.

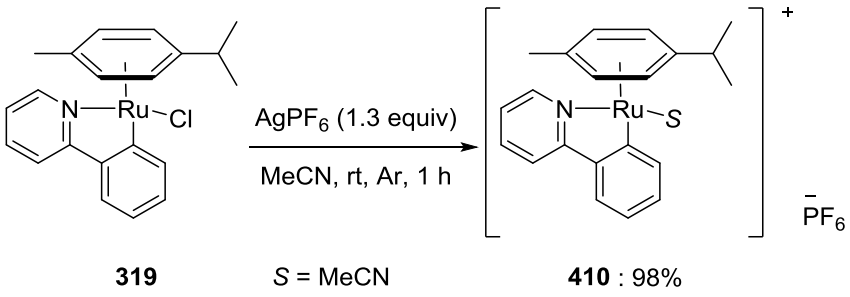
It was decided to synthesise the chlorinated C-H activated complex **319**, as $[RuCl_2(p\text{-cymene})]_2$ contains chlorides in the complex and followed the procedure reported by Dixneuf to synthesise the C-H activated complex **319**.[4] The catalyst $[RuCl_2(p\text{-cymene})]_2$ was reacted with 2 equivalents of 2-phenylpyridine **63** and 4 equivalents of base, KOAc, in dry methanol (MeOH) under argon for 39 hours and gave complex **319** as an orange solid in 89% yield (Scheme 157). Compared to the literature, it was reported complex **319** was afforded in 94% yield in 20 hours, but this difference could be attributed to the fact that the reaction herein was performed in a larger scale, hence the difference in yields. It is noteworthy that for the synthesis of organometallic complexes, it was necessary to perform the reactions under inert atmosphere, as some organometallic complexes

are known to be sensitive to air or are hygroscopic. Therefore, to prevent the ruthenium complexes from decomposition, all of the reactions were performed under inert atmosphere, mostly under argon.



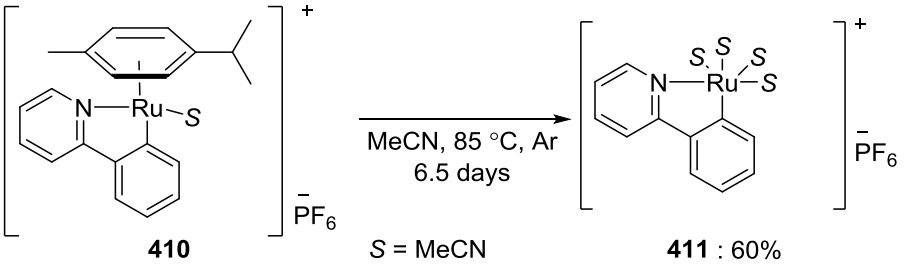
Scheme 157

Next, the chloride was removed from the complex by using a silver salt, $AgPF_6$. A solution of **319** in dry MeCN, was reacted with 1.3 equivalents of $AgPF_6$ at room temperature with stirring and gave the desired complex **410** as a yellow solid in 98% yield (Scheme 158).



Scheme 158

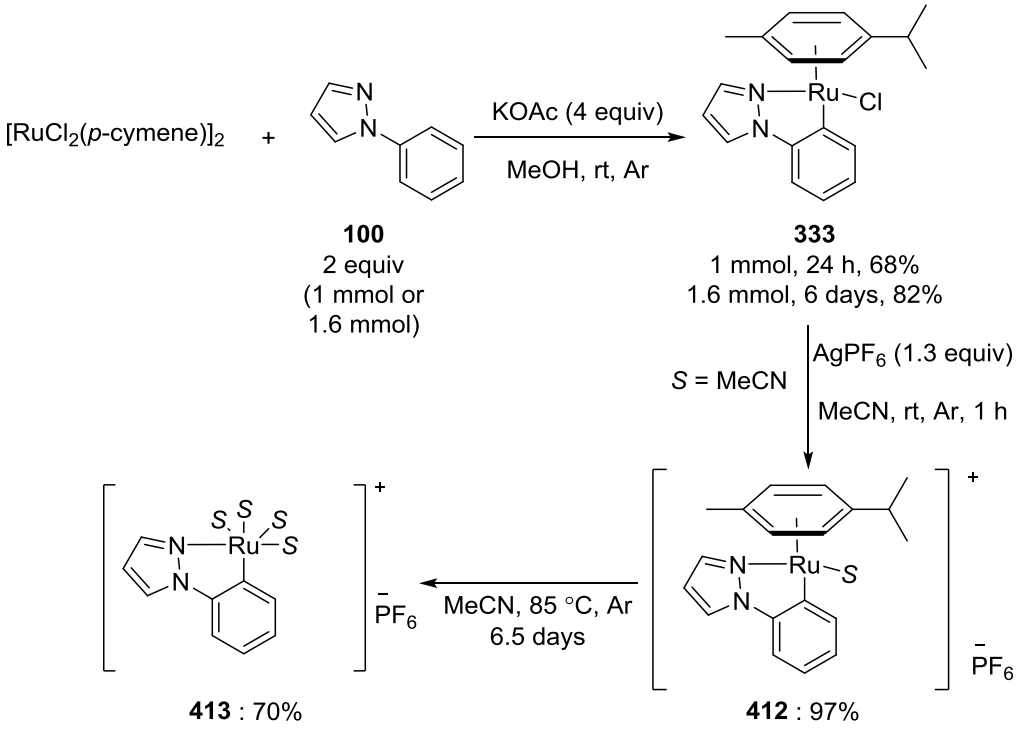
Complex **410** was then heated at 85 °C under an atmosphere of argon for 6.5 days, and afforded complex **411** as a dark green solid in 60% yield (Scheme 159).



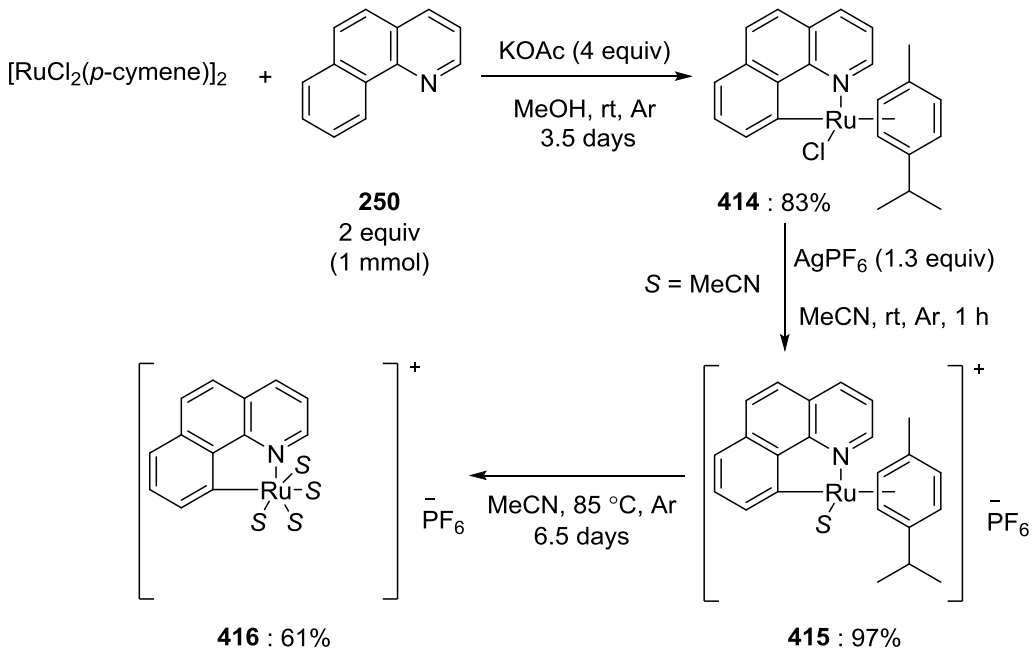
Scheme 159

Derivatives of ruthenium complexes **319**, **410** and **411** of 1-phenylpyrazole and benzo[*h*]quinoline were synthesised using the same procedures as for the synthesis of 2-phenylpyridine-ruthenium complexes (Schemes 160 and 161).

Interestingly, the *ortho*-C-H activation of 1-phenylpyrazole with $[RuCl_2(p\text{-cymene})]_2$ seemed to be affected by the reaction scale, because the reaction performed in a slightly larger scale took a longer duration to complete the reaction, but this was compensated with a higher yield of complex **333** (Scheme 160).



Scheme 160



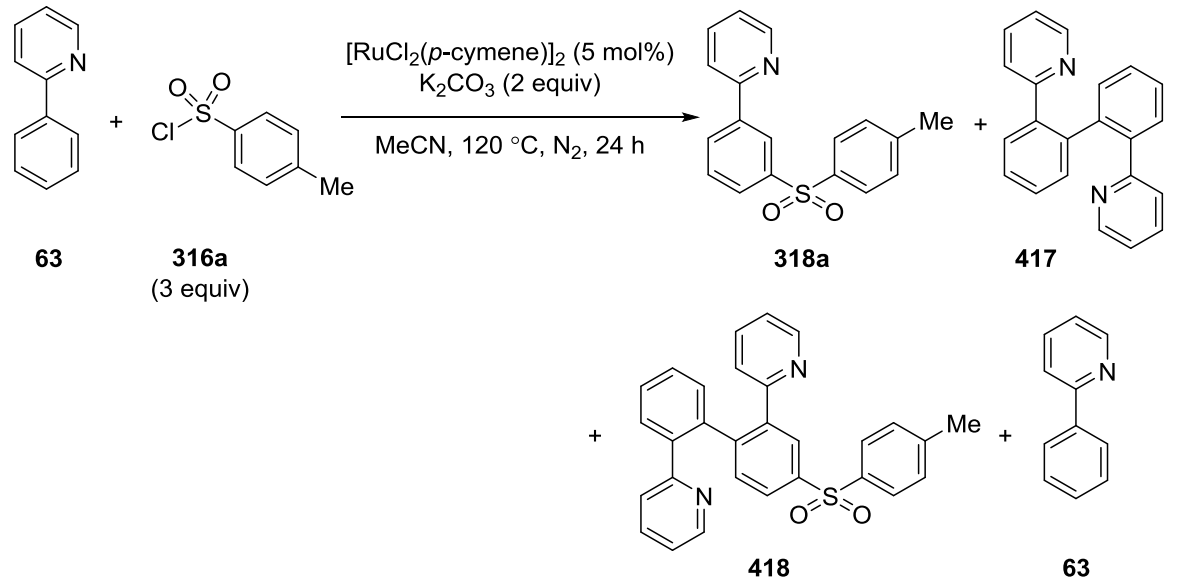
Scheme 161

The *ortho*-C-H activation of the three substrates with a ruthenium catalyst appears to be reacting at different reaction rates. 1-Phenylpyrazole was C-H activated in the shortest amount of time, but it is worth noting that the yield is much lower in comparison to the other two substrates. In addition, it is clearly highlighted that the C-H activation of benzo[*h*]quinoline required the longest reaction time. This work is in agreement with Dixneuf's studies on the C-H activation of nitrogen-containing substrates with a ruthenium complex. In Dixneuf's work it was revealed that the half-life for the C-H activation of 2-phenylpyridine was $t_{1/2}$ = 45 minutes and for 1-phenylpyrazole it was 520 minutes.[2-4] In this regard, it can be proposed that the reactivity for the C-H activation by $[RuCl_2(p\text{-cymene})]_2$ in the presence of a base, KOAc, is in the order of : 2-phenylpyridine>1-phenylpyrazole>benzo[*h*]quinoline.

4.1b. Mechanistic considerations of *meta*-C-H sulfonation

A member of the Frost group, Dr Patricia Marcé-Villa has performed kinetic studies on the ruthenium-catalysed *meta*-sulfonation of 2-phenylpyridine with *para*-toluenesulfonyl chloride (*p*-TsCl) **316a** in MeCN and PrCN independently, as these two solvents provided similar reaction efficiency. Analysis data was carried out by LC-MS at various time intervals for the duration of 24 hours.

In both cases, reactions in MeCN and PrCN have identified four different species in the reaction mixtures, 2-phenylpyridine **63**; *meta*-sulfonated product **318a**; a homodimer of 2-phenylpyridine **417** as well as the heterodimer **418** (Scheme 162). It is noteworthy that during the investigation of the *meta*-sulfonation scope, neither dimer products were isolated, with the exception of the sulfonation of benzo[*h*]quinoline, where the benzo[*h*]quinoline herterodimer **337b** was isolated (Chapter 2).



Scheme 162

The reaction profile of *meta*-sulfonation of 2-phenylpyridine and *p*-TsCl in MeCN is shown in Figure 4. It clearly shows that there was an induction period during the first hour, as product formation was only detected after 2 hours of heating, then 30 minutes later there was a gradual increase in *meta*-product **318a** formation. After two hours, product formation was observed then after 4 hours into the reaction it seems to reach its limit and the curve plateaus. The plateau of *meta*-product at 4 hours, suggest the catalyst is no longer being regenerated possibly due to an accumulation of an inactive ruthenium species such as **411** being formed preventing the catalyst turnover. Dixneuf has also observed in their autocatalysis study the formation of complex **409** after 4 hours of heating and complex **409** was shown to be inactive as a catalyst towards arylation.[2] After 24 hours of heating, LC-MS detected 58% conversion of the *meta*-sulfonated product **318a** was formed and 33% of starting material **63** remained in the reaction mixture. Interestingly, between 4 and 6 hours into the reaction, the formation of the two dimers **417** and

418 started to appear, by the end of the reaction both dimers were formed in only a small amount, but the heterodimer **418** is formed in a slightly higher quantity than the homodimer **417**.

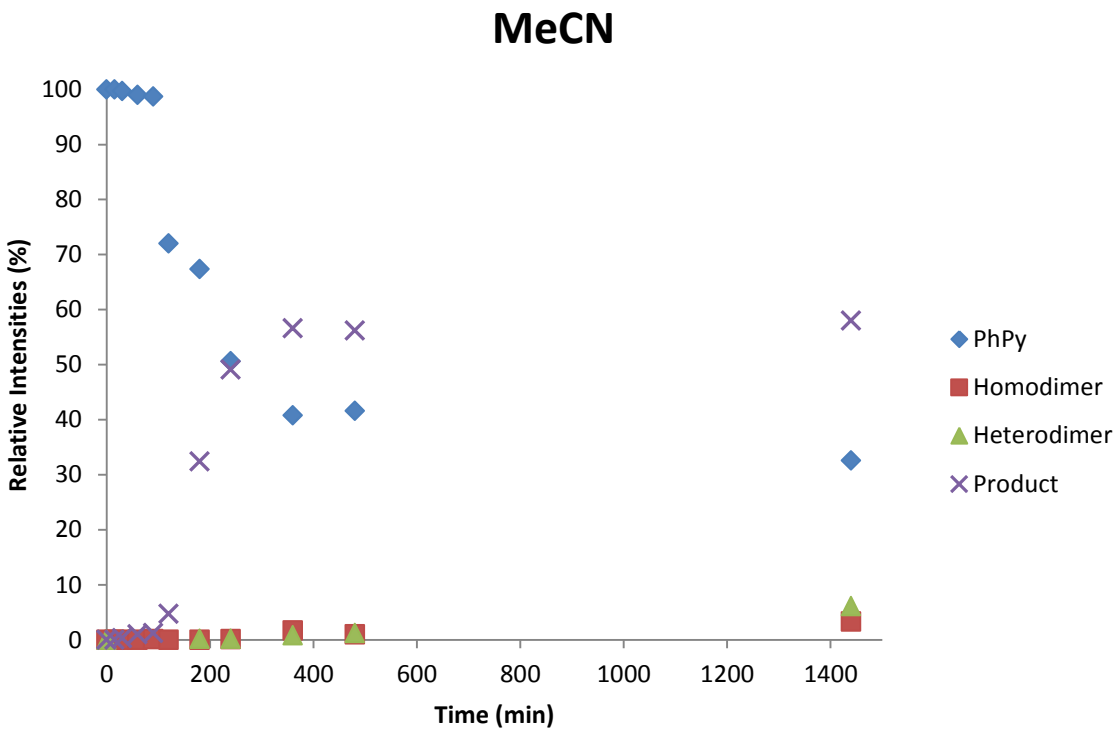


Figure 4. Kinetics reaction profile in MeCN

In comparison to the reaction profile performed in PrCN at 120 °C (Figure 5), there are noticeable differences to the reaction profile in MeCN. Firstly, there was a much shorter induction period of 15 minutes before any products were detected. In this regard, it suggests that reaction in PrCN requires less time to form the active catalytic species to catalyse the reaction, whereas in MeCN, it requires more time to form the active catalyst species to enable C-H *meta*-sulfonation to take place. After this time lag, the *meta*-product **318a** was found to be formed exponentially, however, after 2 hours of heating, the product formation of **318a** began to slow down and the curve seemed to reach a stationary phase. Both the homo and heterodimers **417** and **418** were detected 30 minutes into the reaction, in contrast to the reaction in MeCN, the two dimers were only detected in the later stages of the reaction. More importantly, is that both the homo and heterodimers were formed in a significant amount compared to the reaction in MeCN. This was also observed in chapter 2, when PrCN was used as the reaction solvent under the sulfonation conditions, by-products were observed in both the crude ^{1}H NMR spectrum and TLC analysis. From this graph, it clearly shows that the reaction in PrCN have a higher efficiency compared to

MeCN, however there is a drawback, where a higher conversion of by-products were formed when PrCN is used as the solvent, which could hinder the purification of products. This accelerating effect in PrCN seems to enhance the productivity of the *meta*-product as well as the two by-products.

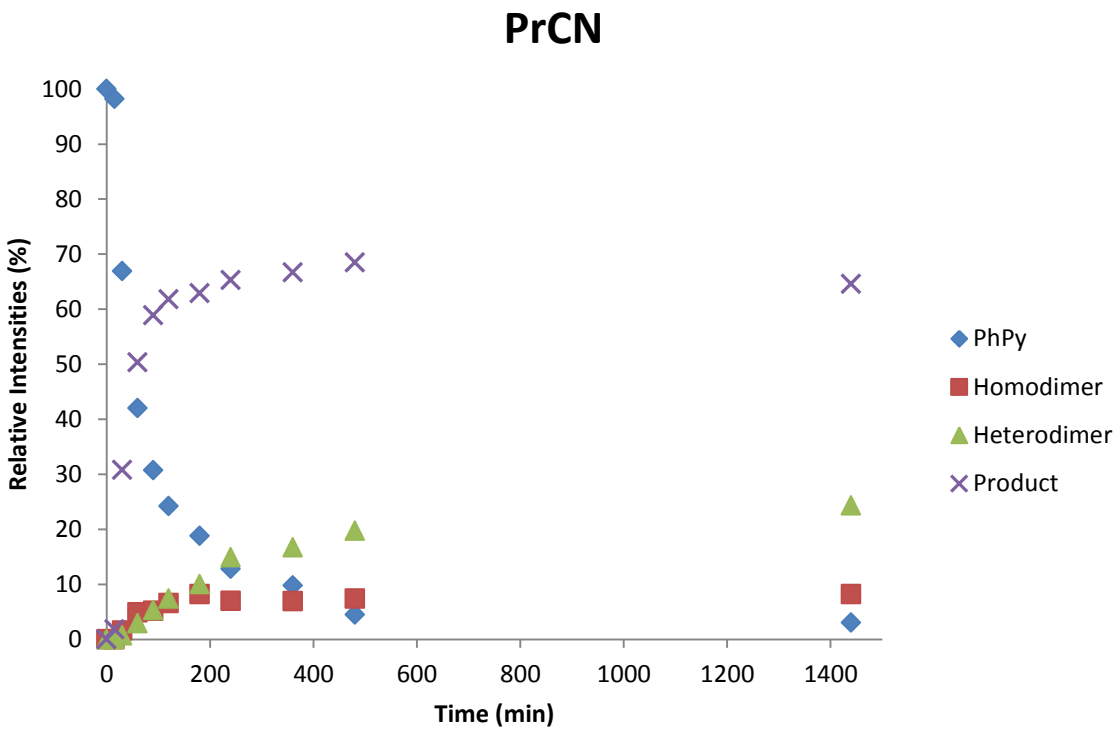


Figure 5. Kinetics reaction profile in PrCN

The next graph is a comparison of 2-phenylpyridine consumption in MeCN and PrCN (Figure 6). Both reactions adopts a sigmoid-like curve, where there is an initial induction period before any of the substrate is consumed. The difference between the two reaction solvents is the induction period and the reaction rate. Reaction in PrCN has a significantly shorter induction period, and the rate at which the starting material is consumed is at a much faster rate in comparison to the reaction in MeCN. Another point to note is that the rate of consumption is faster in PrCN, as the homo and heterodimers **417** and **418** were formed at the same time as *meta*-product **318a** formation (Figure 5). Whereas with MeCN, 2-phenylpyridine consuption was not only slower but also, the homo and heterodimers **417** and **418** were only formed around after 6 hours of heating, hence the slight increase at the end of the curve for MeCN.

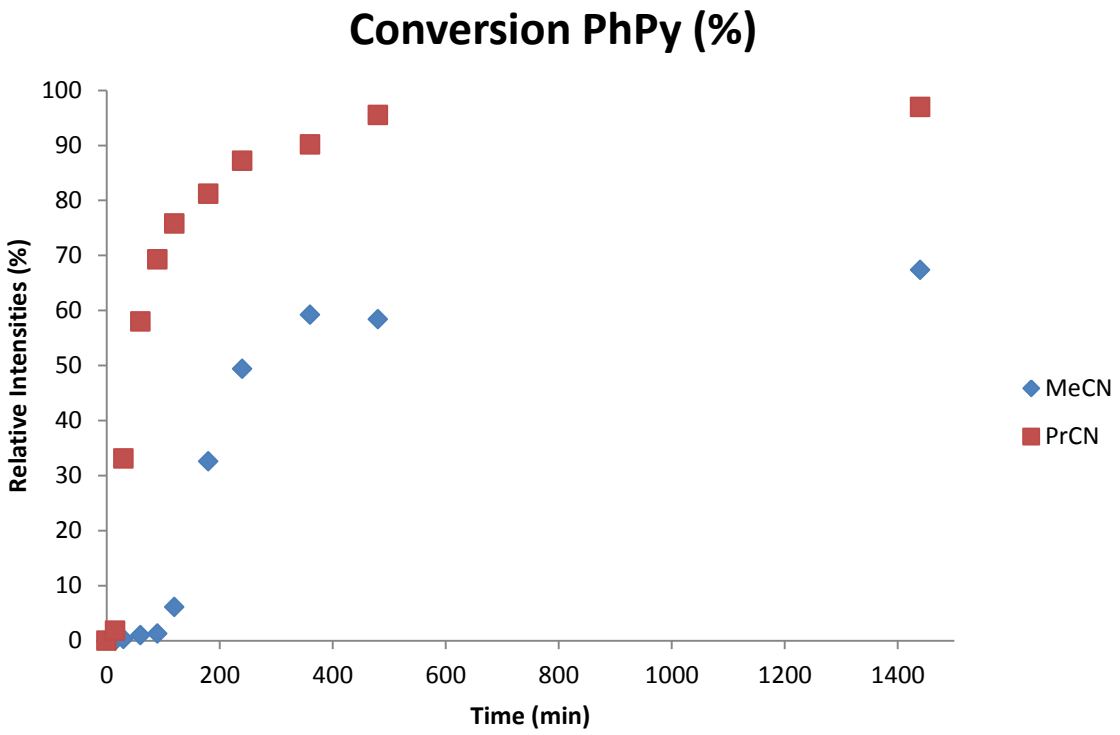


Figure 6. Comparison plot of 2-phenylpyridine consumption in MeCN and PrCN

Figure 7 show a comparison plot of the *meta*-sulfonation product **318a** formation between the reactions in MeCN and PrCN. Both reactions adopts a sigmoid-like curve, however, it clearly indicates that reaction in PrCN has formed the *meta*-product **318a**, not only in a faster rate but also with a slightly higher conversion of *meta*-product **318a**. Although there is a significant difference in the reaction rates between the two solvents, however it is noteworthy that reaction in PrCN has a higher conversion of by-products formed as well.

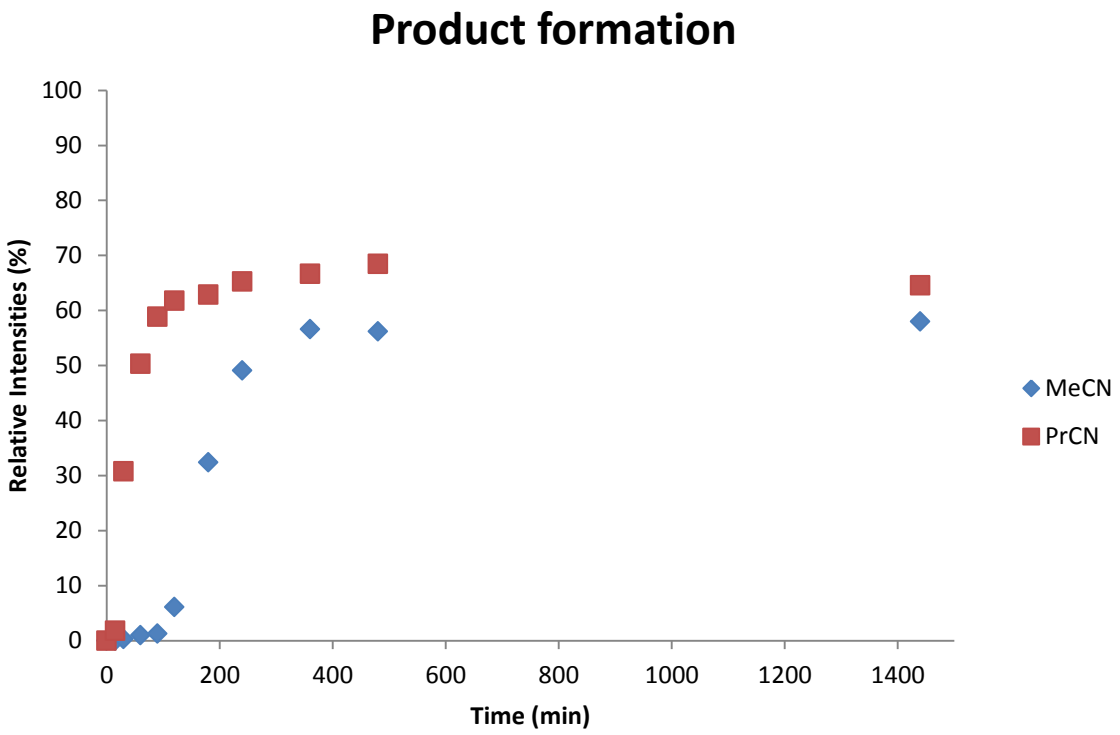
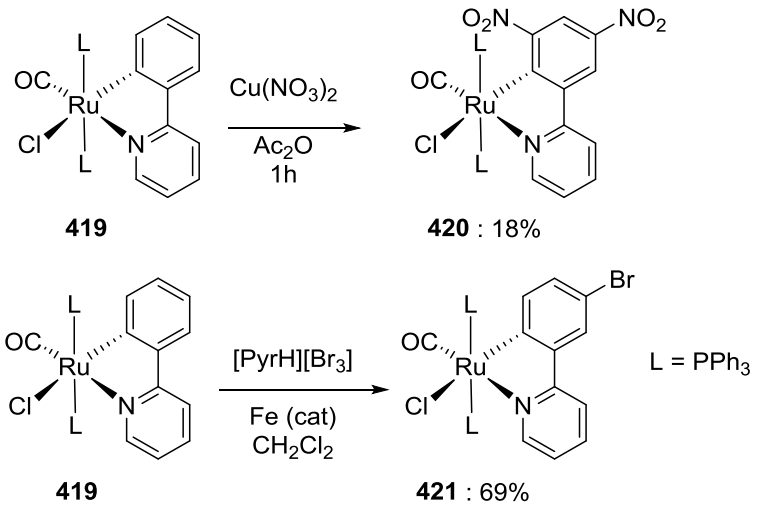


Figure 7. Comparison plot of product formation

In Chapter 2, it was hypothesised that the *meta*-sulfonation of 2-phenylpyridine operates by the nitrogen directing group forming a stable Ru-C_{aryl} σ-bond which induces a strong *para* directing effect, resulting in electrophilic aromatic substitution, S_EAr, selectively on the 4-position, *para* to the Ru-C_{aryl} σ-bond. Roper *et al.* first reported this phenomenon, and it was found that by stabilising the M-C σ-bond *via* chelation, it activates the aromatic ring, acting as a directing group, which leads to electrophilic substitution to take place *para* to the Ru-C_{aryl} σ-bond (*meta*-position).[5-7] This phenomenon was demonstrated with Os(II) and Ru(II) complexes, and of particular interest are the examples reported utilising the Ru complexes. Complex **419** containing a 2-phenylpyridine ligand, can undergo electrophilic substitution *para* to the Ru-C σ-Bond. The first example shows that treatment of complex **419** under nitration conditions provides the di-nitrated product **420**. Introduction of the first nitro group did not deactivate the phenyl ring toward further nitration, which indicates that complex **419** is activated at both the *para* (to the Ru-C_{aryl} σ-bond) and *ortho* positions. Bromination can also be performed on complex **419** with [PyH][Br_3] in the presence of catalytic amounts of iron powder led to the brominated product **421** with high regioselectivity. It is noteworthy, that under the bromination conditions, only the mono brominated complex **421** is produced and the yield is considerably higher in comparison to the nitration reaction (Scheme 163).



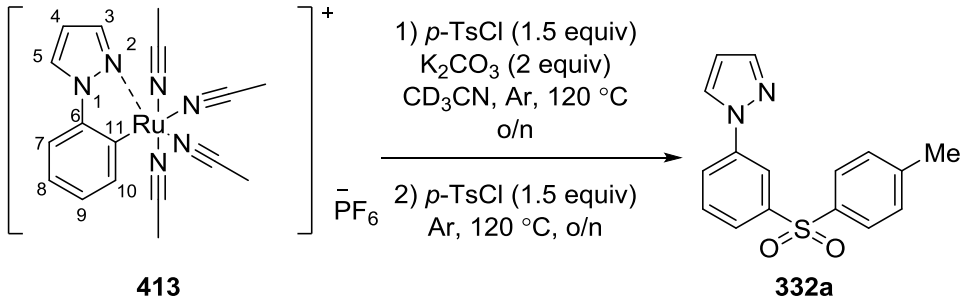
Scheme 163

The study by Roper provides evidence of *meta*-C-H functionalisation *via* para activation from the Ru-C_{aryl} σ-bond, therefore it was decided to attempt stoichiometric experiments with the ruthenium-substrate complexes under *meta*-sulfonation conditions to achieve *meta*-C-H sulfonation stoichiometrically. During this mechanistic study, other members of the Frost group were also working on the mechanistic of the *meta*-sulfonation of 2-phenylpyridine-ruthenium complexes with *p*-TsCl. Therefore it was decided at the time to focus on the mechanistic study on 1-phenylpyrazole and benzo[*h*]quinoline. As it was of interest to understand why these two substrates reacted poorly under the *meta*-sulfonation conditions, however the reactivity switched under the acylation conditions, where both 1-phenylpyrazole and benzo[*h*]quinoline were found to undergo *ortho*-acylation with alkyl and aryl acid chlorides.

As it is already known in the literature that the *p*-cymene ligand dissociate at high reaction temperatures, and since the reaction is at 120 °C, it was decided to use the fully solvated ruthenium-substrate complexes for the *meta*-sulfonation experiments, with *p*-TsCl as the coupling partner.[8]

Complex **413** was reacted with 1.5 equivalents of *p*-TsCl and 2 equivalents of K_2CO_3 in CD_3CN in a Young's tube and sealed under an atmosphere of argon and the reaction was followed by ^{1}H NMR spectroscopy. (Structure 413 was assigned by 1D and 2D ^{1}H and ^{13}C NMR spectroscopy). The reaction tube was heated at 120 °C overnight and the ^{1}H NMR spectrum (Figure 8, spectrum b)

revealed the appearance of two new ruthenium-phenylpyrazole species. One is the *meta*-sulfonated complex **422** proposed from the ^{1}H NMR spectra, which gave 66% conversion. There was 19% of the starting material complex **413** present and 14% of a new ruthenium-phenylpyrazole complex. Then another addition of *p*-TsCl (1.5 equivalents) was added into the Young's tube and heated overnight (Figure 8, spectrum c) show that there are two sets of H4 protons present, and it seems to have shifted slightly upfield, one is the demetallated sulfonated product with 73% conversion and the other peak is 1-phenylpyrazole with 26% conversion (Figure 9). (Scheme 164)



Scheme 164

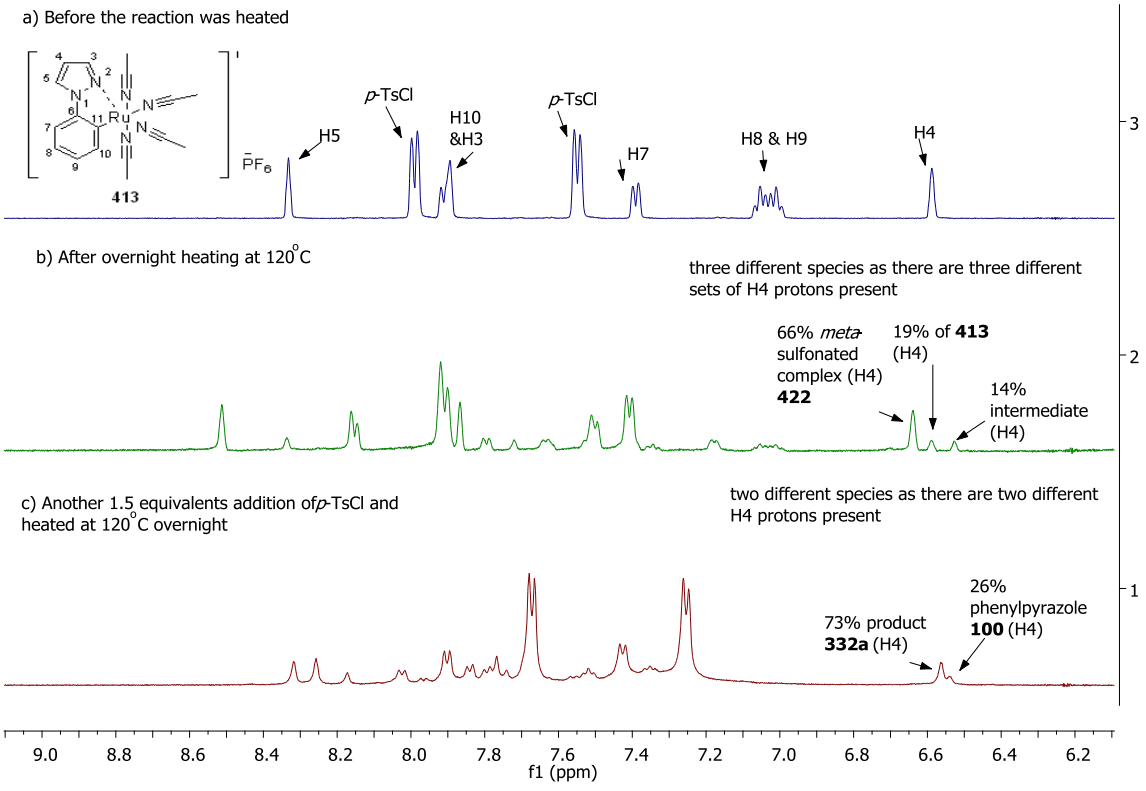
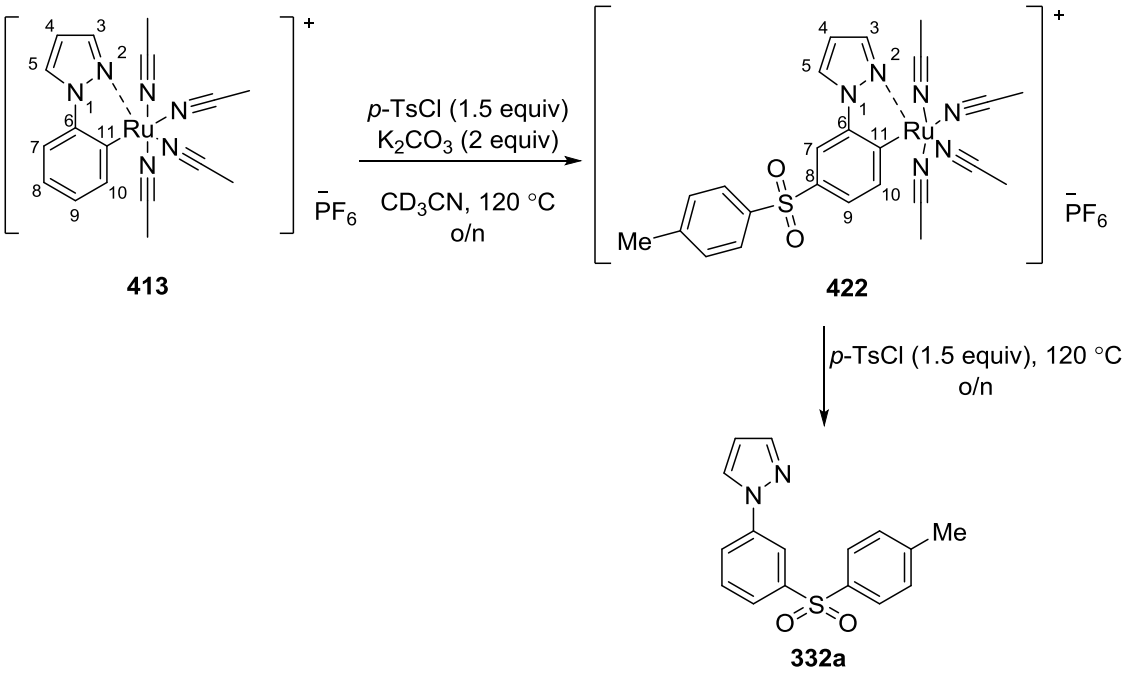


Figure 8

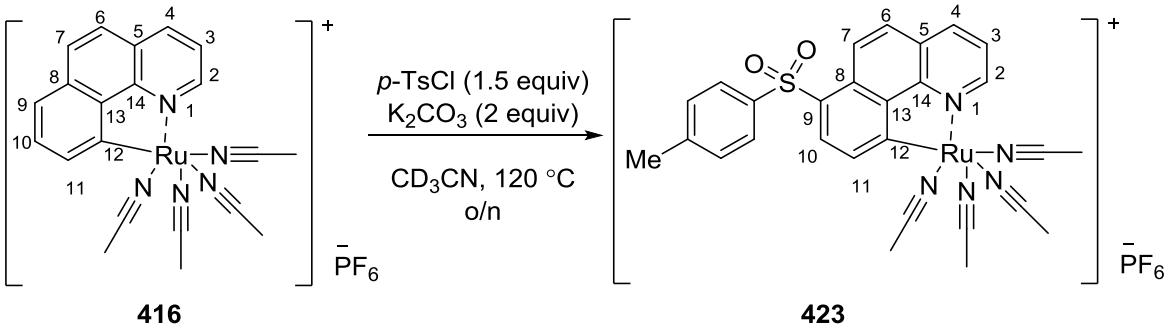
The overall stoichiometric reaction for the *meta*-sulfonation of complex **413** is shown on scheme 165.



Scheme 165

From the NMR experiments, it clearly shows that, despite the fact that the substrate is already C-H activated, the sulfonation reaction does not go to completion, and this suggests complex **413** is highly stable, which makes it difficult to react towards incoming electrophiles.

Next, benzo[*h*]quinoline-Ru complex **416** was reacted under the *meta*-sulfonation conditions in a Young's tube (Figure 9). Interestingly, after heating the reaction overnight, unlike phenylpyrazole, the complex **416** was fully consumed and two new ruthenium-benzo[*h*]quinoline complexes appears in the spectrum (Figure 9, spectrum b), with a ratio of 3.4:1. The major complex was elucidated with 1D and 2D ^{1}H and ^{13}C NMR experiments and it was deduced to be the *meta*-sulfonated benzo[*h*]quinoline complex **423** which is still cyclometallated to the ruthenium as the Ru-C quaternary carbon (position 14) is present in the ^{13}C NMR spectrum at 202.0 ppm. (Scheme 166)



416 **423**

Scheme 166

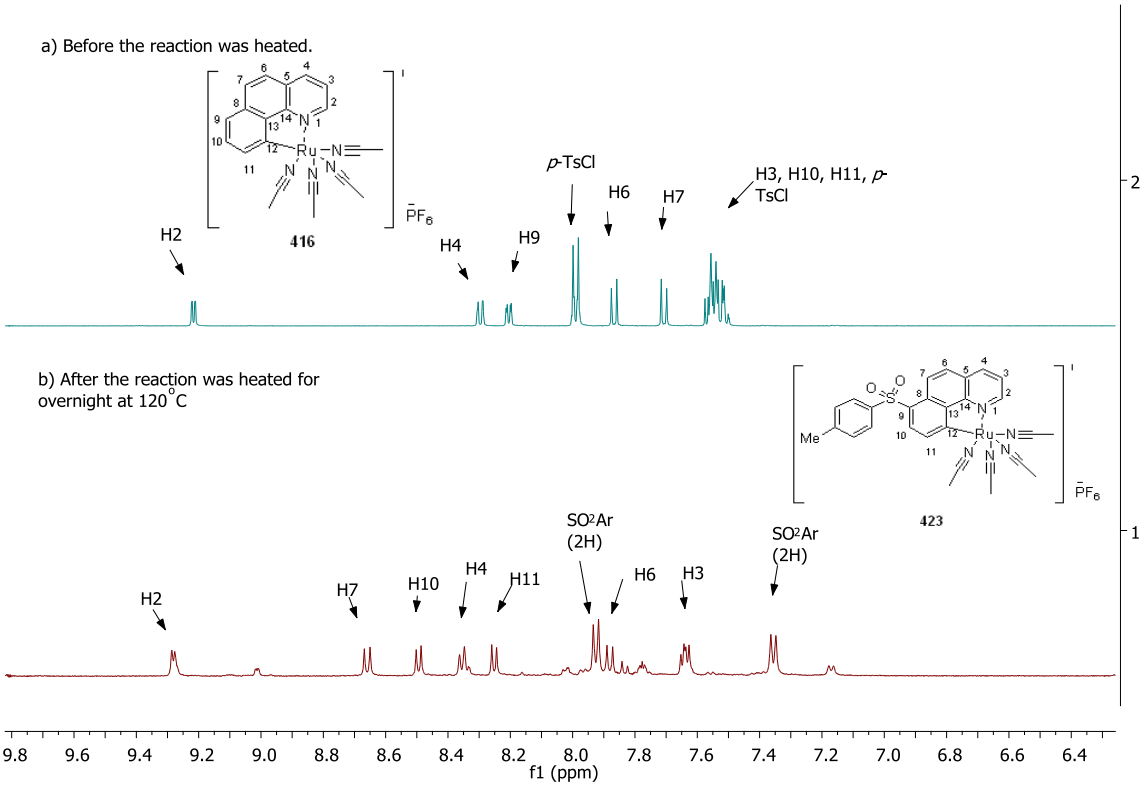
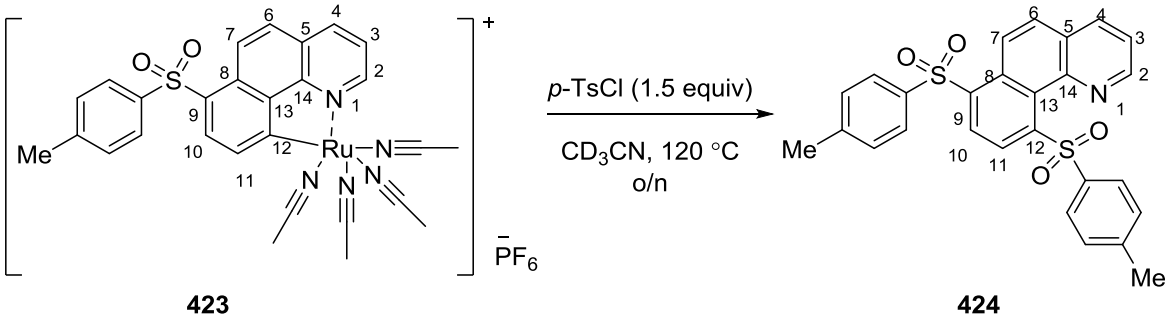


Figure 9

Then another 1.5 equivalents of *p*-TsCl was added into the reaction tube and was heated at 120 °C overnight. From Figure 11 it clearly shows that two new benzo[*h*]quinoline species are formed and the previous sulfonated benzo[*h*]quinoline-ruthenium complex **424** is fully consumed in the reaction, with a ratio of 1.7:1 of the two new species (Figures 10). From the ^{13}C NMR spectrum, a downfield Ru-C peak could not be found, which suggests the *meta*-sulfonated benzo[*h*]quinoline has been demetallated in the reaction. (Scheme 167)



423 **424**

Scheme 167

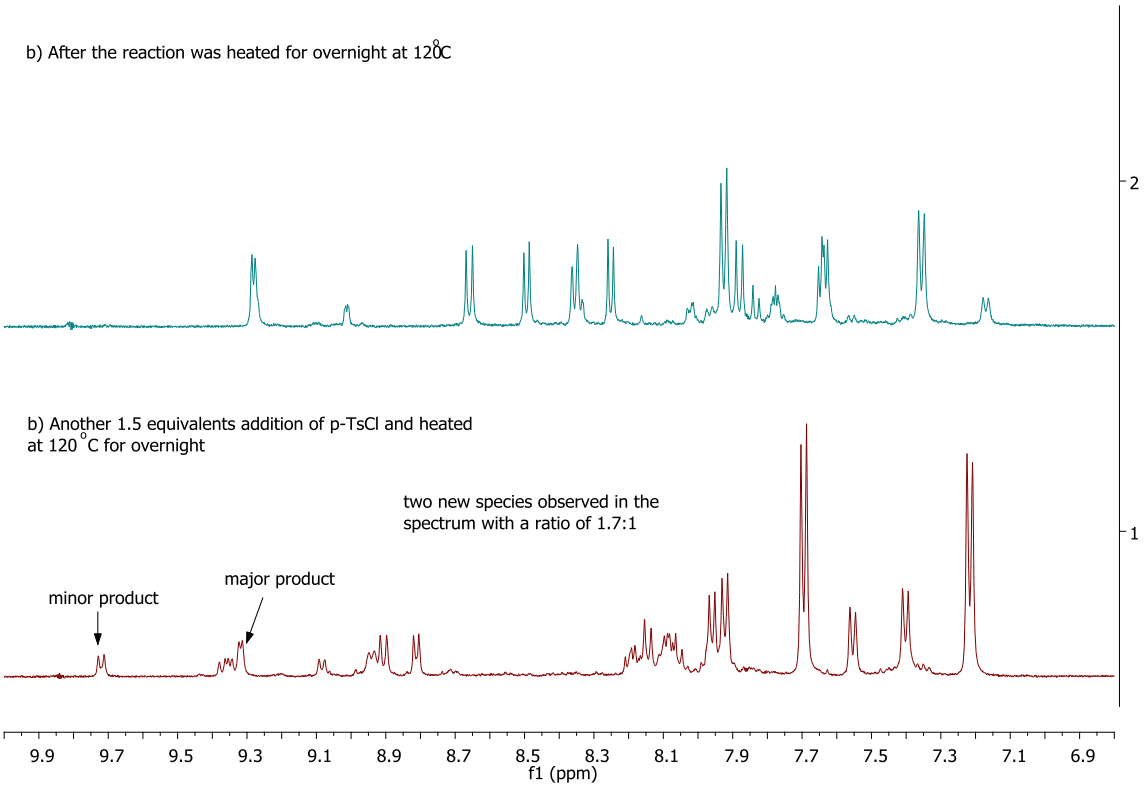


Figure 10

A closer inspection of the ^{1}H NMR spectra seems to show two different sets of *para*-toluene protons present and both sets of integrals are equal to four protons (2 + 2), this suggests that two molecules of *para*-toluene are in the major product (Figures 11). Although both sets of *para*-toluene doublets are inequivalent, however they are in similar environment as the doublets are close together, and less than 0.5 ppm apart. Because of the similar environments of which the doublets are located, and the fact that the molecule is not symmetrical, on the basis of the ^{1}H and

^{13}C 1D and 2D NMR spectra, a structure was proposed for the final demetallated product as **424**. Structure **424** contains two sulfones, one is on the *meta* position and the other is on the *ortho* position. There is also an excess of *p*-TsCl present as well. In this regard, it appears that the extra equivalence of *p*-TsCl is necessary for the demetallation process in order to obtain the *meta*-sulfonated product (Scheme 168).

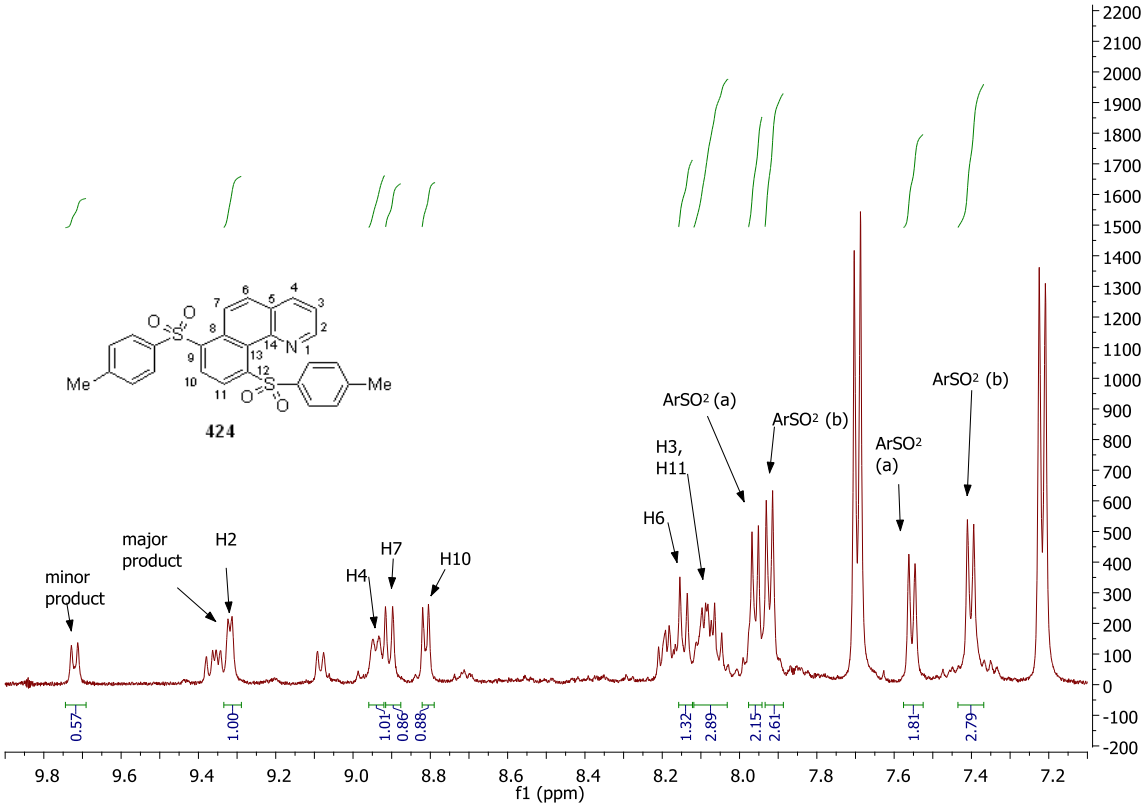
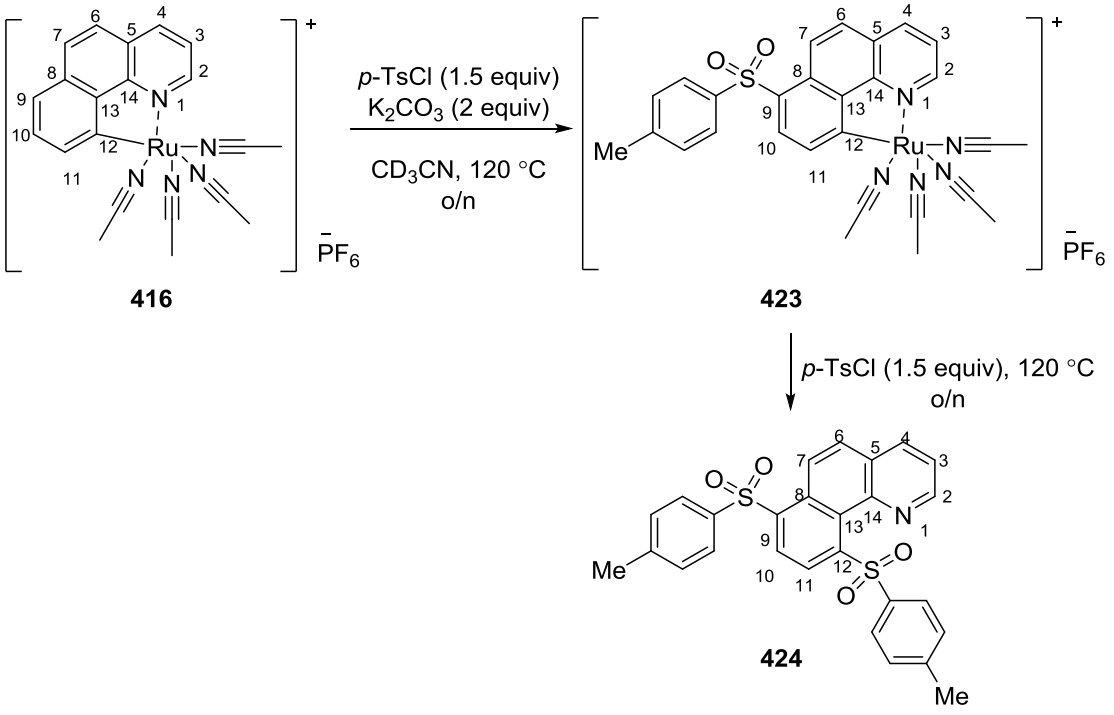
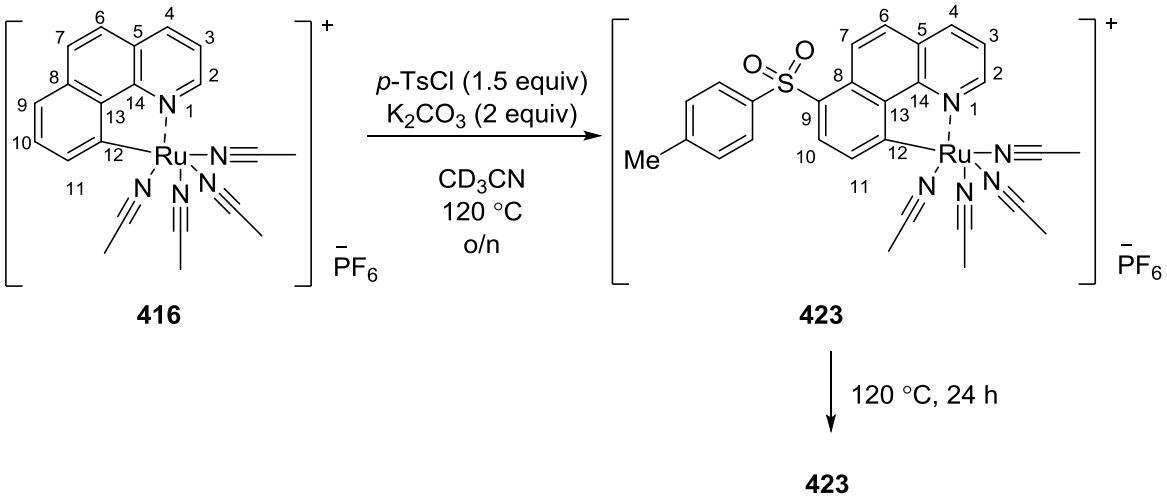


Figure 11



Scheme 168

It was decided to replicate the reaction but rather than adding the extra addition of *p*-TsCl after 15 hours, the reaction was heated with prolonged period of 48 hours, to investigate the stability of this sulfonated-benzo[*h*]quinoline-ruthenium complex **423**. After 48 hours of heating, no differences were observed in the ^{1}H NMR spectrum; both the *meta*-sulfonated complex **423** and the intermediate complex were still present with same ratio (Figure 12). (Scheme 169)



Scheme 169

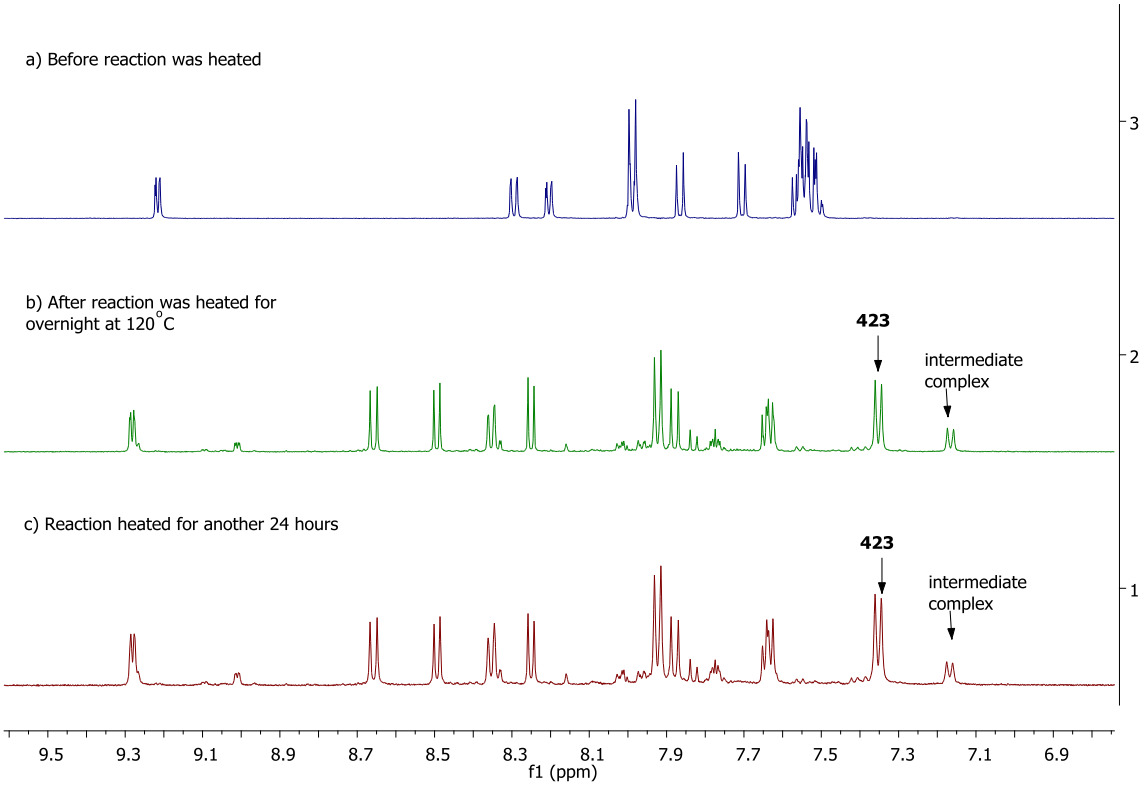
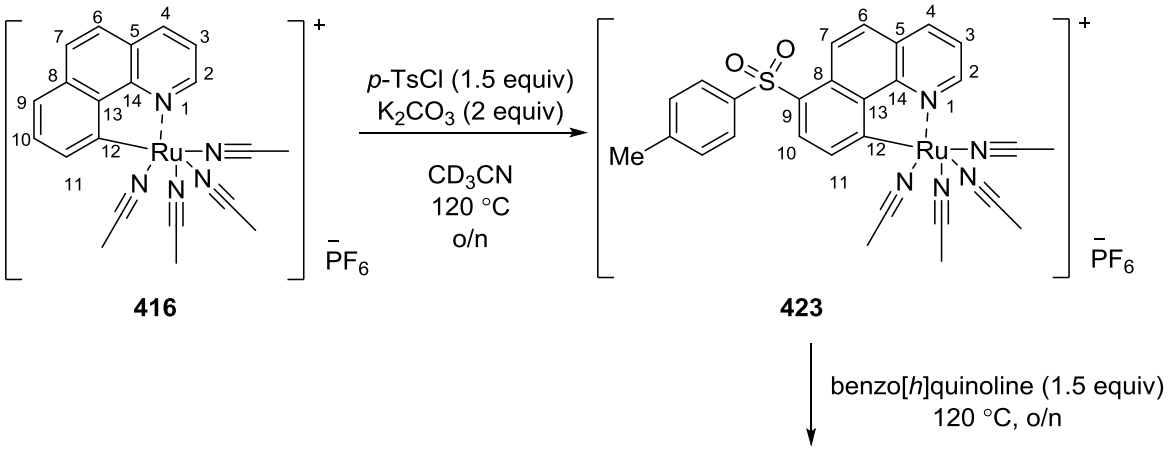


Figure 12

In chapter 2, it was found that reaction of benzo[*h*]quinoline **250** with *p*-TsCl **316a** under the *meta*-sulfonation conditions provided two products, the *meta*-sulfonated benzo[*h*]quinoline **337a** as well as a heterodimer **337b**. Because of this result, it was decided to attempt to synthesise this heterodimer **337b** stoichiometrically by using the *meta*-sulfonated benzo[*h*]quinoline complex. After the formation of the *meta*-sulfonated benzo[*h*]quinoline-ruthenium complex **423**, 1.5 equivalents of benzo[*h*]quinoline was added into the Young's tube and heated overnight (Scheme 170). Unfortunately, no new peaks were observed in the ^{1}H NMR spectrum, however, the ratio of the minor intermediate complex seemed to have increased and the opposite effect was observed for the sulfonated benzo[*h*]quinoline complex **423** (Figure 13). In addition, complex **423** was still intact as the ^{13}C NMR spectrum shows the quaternary Ru-C signal at 202.0 ppm.



Scheme 170

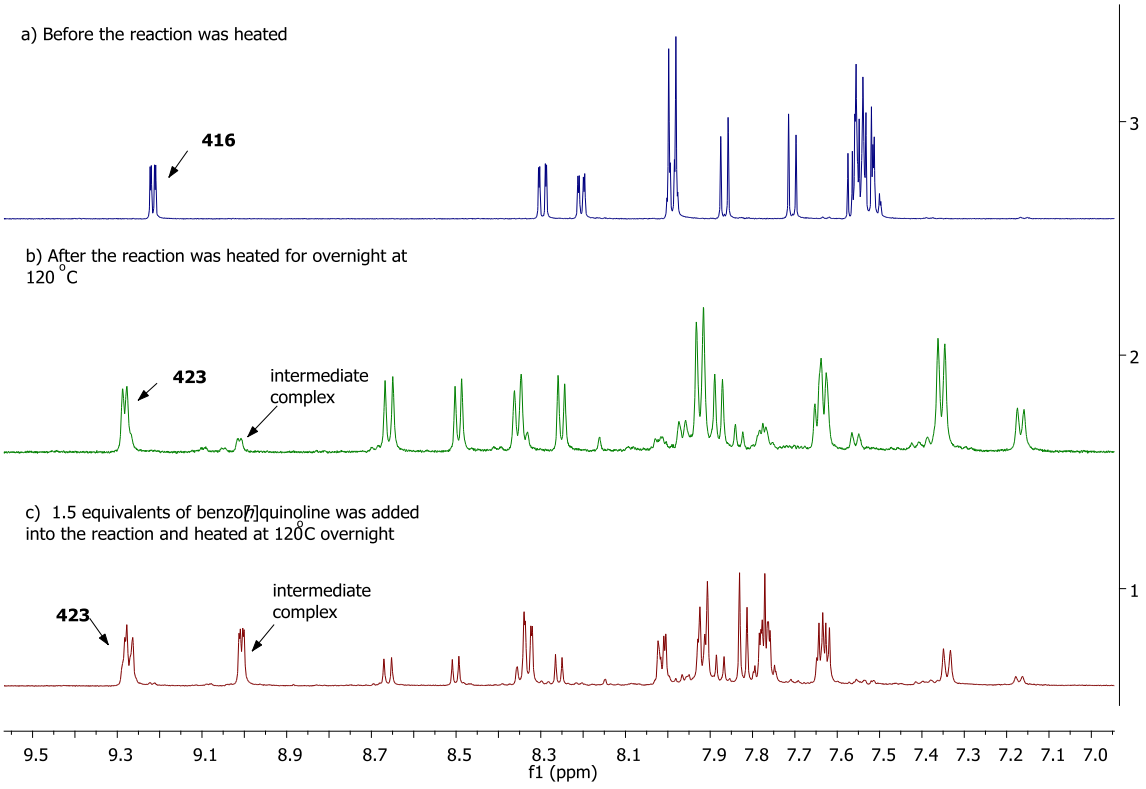
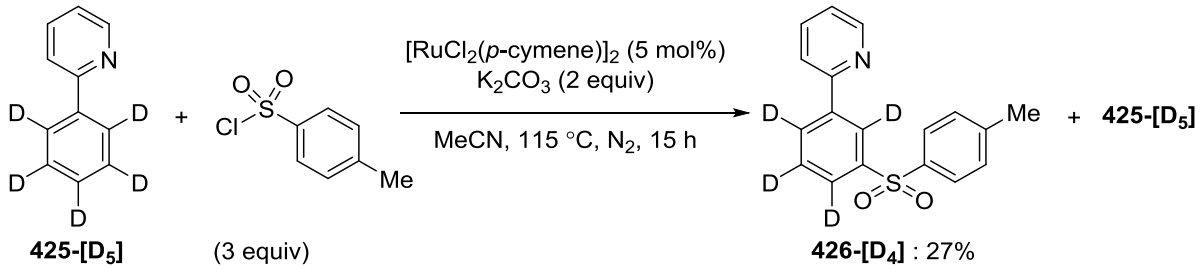


Figure 13

Both the *meta*-sulfonation of phenylpyrazole-ruthenium complex **413** and benzo[*h*]quinoline-ruthenium complex **416** reactions were performed in a larger scale, to attempt to isolate the *meta*-sulfonated substrate-ruthenium complexes and to obtain crystal structures as further evidence to verify the structures. Unfortunately, there were difficulties in purifying the *meta*-sulfonated complexes, therefore unable to obtain the products cleanly for single crystal X-ray analysis. Nevertheless, both complexes **413** and **416** have demonstrated that it could undergo

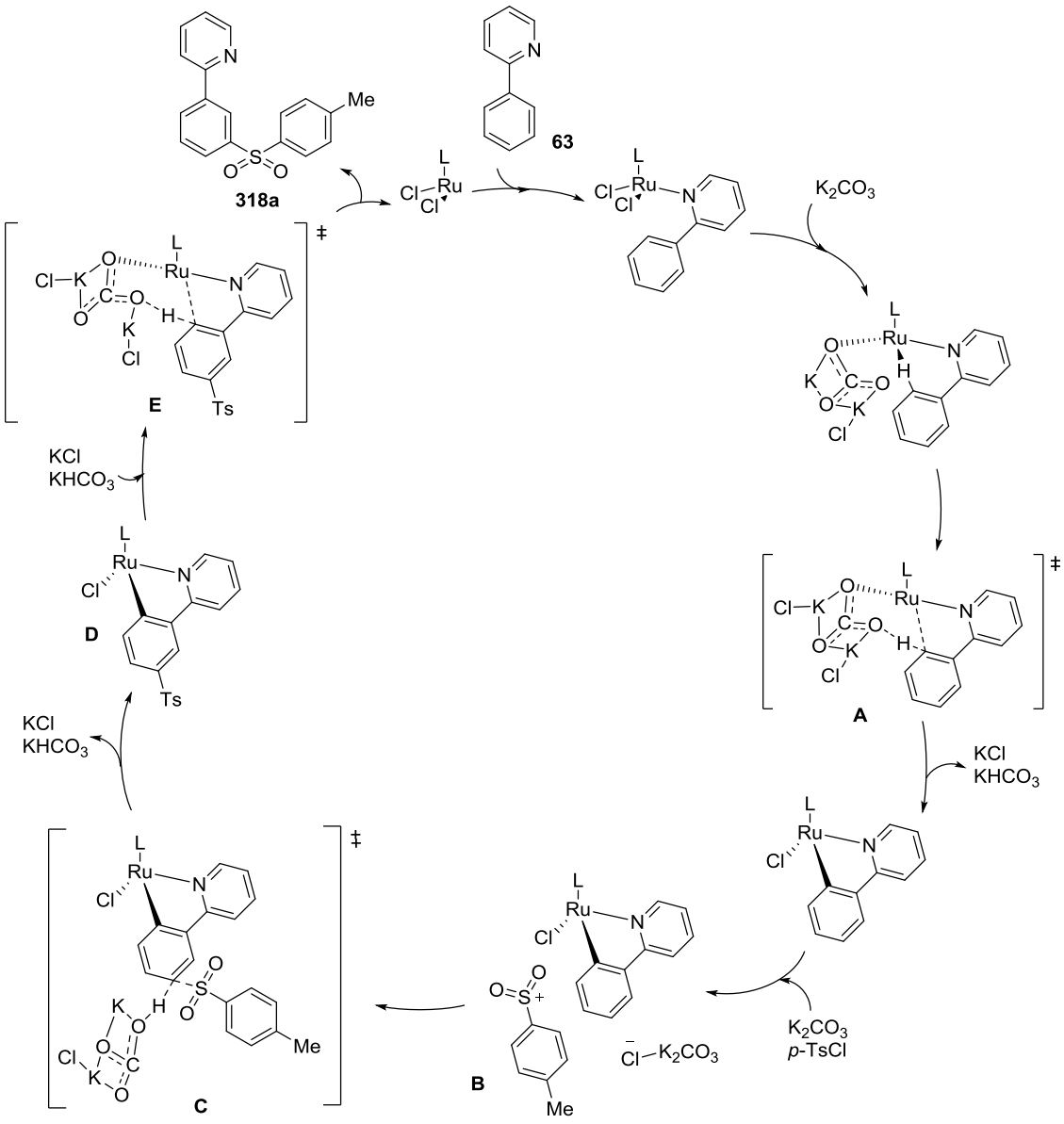
sulfonation *para* to the ruthenium-carbon bond, which suggests the reaction is *via* an σ-activation pathway, in which the Ru-C bond acts as a directing group, directing the electrophile to substitute on the position *para* to the Ru-C_{aryl} σ-bond.

Previous work in the Frost group by Dr Ourida Saidi has shown that isotopically labelled 2-phenylpyridine **425-[D_5]** showed no sign of D/H exchange from adventitious water or solvent.[9] Treatment of **425-[D_5]** under the standard *meta*-sulfonation conditions, after 10 hours of heating, the *meta*-sulfonation product **426-[D_4]** was afforded in 27% yield along with unreacted **425-[D_5]** (Scheme 171). In addition a kinetic isotope effect (k_H/k_D = 3.0) which is kinetically significant. These experimental findings suggest that C-H bond cleavage is most likely the rate-determining step.



Scheme 171

Recently, Fu and co-workers reported a DFT study on the *meta*-sulfonation of 2-phenylpyridine.[10] It was revealed that the rate-determining step is the *ortho* C-H activation and the DFT calculated kinetic isotope effect (KIE = 4.8) is in agreement with the isotope effect observed experimentally (KIE = 3.0). It was also found that electrophilic substitution, and not the chelating group, determines the regioselectivity, which is indicative of an induced *para*-directing effect of Ru-C_{aryl} σ-bond. In addition, DFT calculations revealed that K_2CO_3 plays an important role in the catalytic cycle (Scheme 167). Firstly, K_2CO_3 is involved in the *ortho* C-H activation (**A**), and it stabilises the *p*-TsCl dissociating intermediates (**B**). Then K_2CO_3 is engaged in the electrophilic substitution step (**C**), for the C-H bond cleavage, but that is unusual, as in conventional S_EAr, a base is not needed in the electrophilic substitution process. Finally, K_2CO_3 is involved in the demetallation step (**E**) to obtain the *meta*-sulfonated product **318a**. Interestingly, DFT calculations of the *meta*-sulfonation in different reaction solvents greatly influence the rate-determining step. In MeCN, the rate-determining step is the *ortho* C-H activation, in contrast, in toluene and dioxane, it changes to *p*-TsCl dissociation.

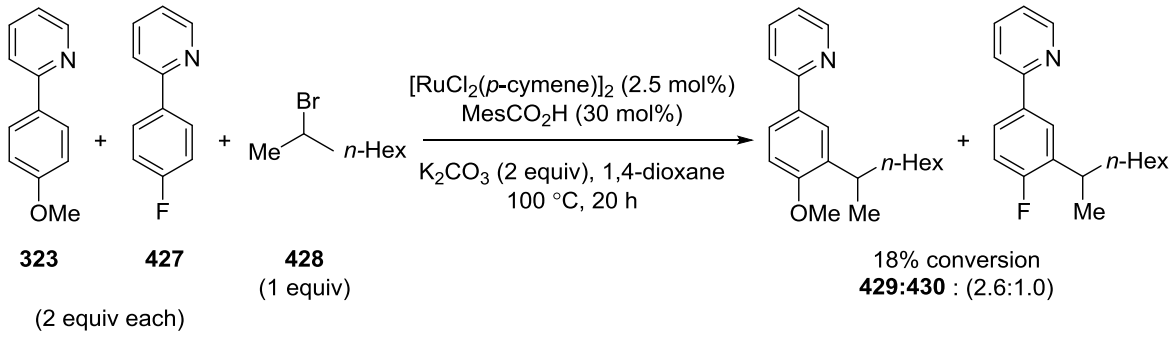


Scheme 172

Whilst our work was in progress, Hofmann and Ackermann have reported a *meta*-selective C-H bond alkylation on heteroarenes with secondary alkyl haildes using the *in-situ* generated well-defined ruthenium(II) biscarboxylate complex [Ru(CO_2Mes)$_2$(*p*-cymene)] **80**.[11] It was a follow-up study on their previous work on ruthenium(II) catalysed C-H alkylation, as described in Chapter 1, Ackermann reported an *ortho*-C-H alkylation reaction with primary alkyl halides.[12] However, when the alkyl halide was switched to a secondary halide the regioselectivity of the product is switched to the *meta*-alkylated product. Similar to our *meta*-sulfonation, Ackermann employs a ruthenium(II) catalyst to perform the C-H functionalisation and it is believed that Ackermann's *meta*-alkylation follows a similar mechanistic pathway to our *meta*-sulfonation reaction. As

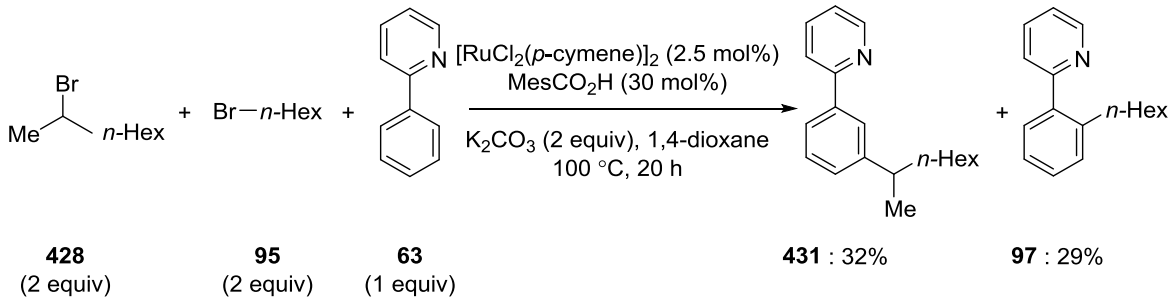
Ackermann has proposed that, the *meta*-alkylation is *via* a remote σ-activation pathway that leads to the *meta*-C-H functionalisation.

In their study, mechanistic insights were gained from various intermolecular competition experiments. Intermolecular competition experiments with differently substituted arenes found that the more electron-rich arene reacts preferentially, thereby indicating an electrophilic-type activation pathway (Scheme 168). In comparison to the *meta*-sulfonation, electron-deficient substrates were unreactive. In the *meta*-sulfonation study, electron-rich substrates were compatible substrates, however, the reactivity was not as efficient compared to the unsubstituted 2-phenylpyridine.[9]



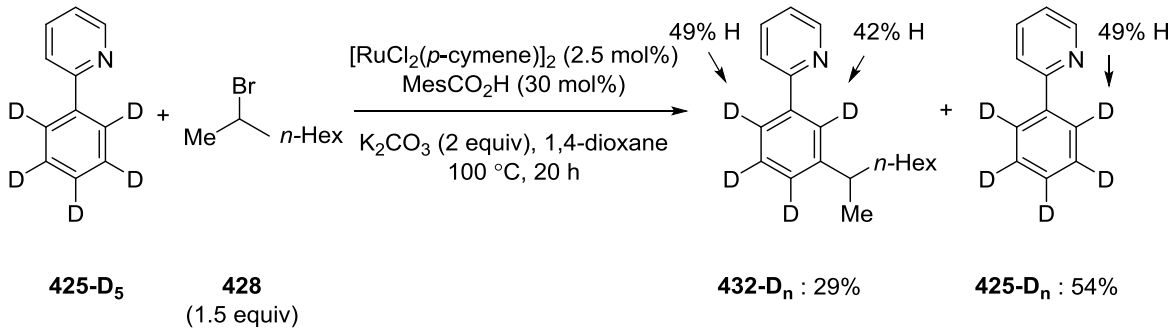
Scheme 173

Intermolecular competition experiments between primary and secondary alkyl halides with 2-phenylpyridine revealed that the electrophile determines the regioselectivity of the products, as primary alkyl halide provided the *ortho*-product **97** and secondary halides gave the corresponding *meta*-product **431** (Scheme 174). The authors reasoned the difference in regioselectivity was due to the varying steric interactions and the electrophilicities of primary and secondary alkyl halides. This rationalisation can be applied to our *meta*-sulfonation and *ortho*-acylation reactions, as sulfonyl chlorides and acid chlorides have different steric interactions and electrophilicities as well.

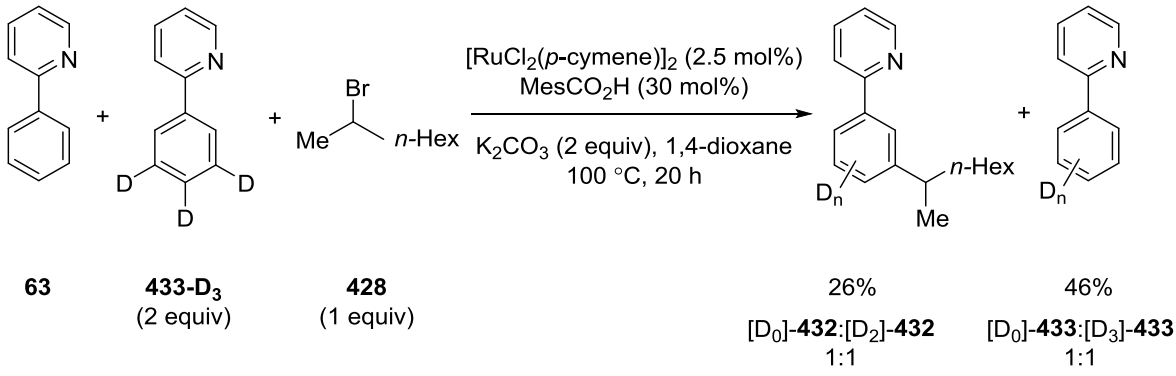


Scheme 174

Interestingly, in the deuterium experiments, isotopically labelled **425**-D_5 underwent D/H exchange by adventitous water in the presence of stoichiometric base and the additive $MesCO_2H$, which suggests the *ortho*-C-H metallation to be reversible in nature (Scheme 175). In addition, the partially deuterated **434**-D_3 also underwent D/H exchange (Scheme 176). Both experiments are indicative that the C-H bond cleavage is not kinetically relevant and it is not the rate-determining step. Whereas this result was not observed in the *meta*-sulfonation as mentioned before in previous work in the group, as no D/H exchange was observed under the *meta*-sulfonation conditions.[9]

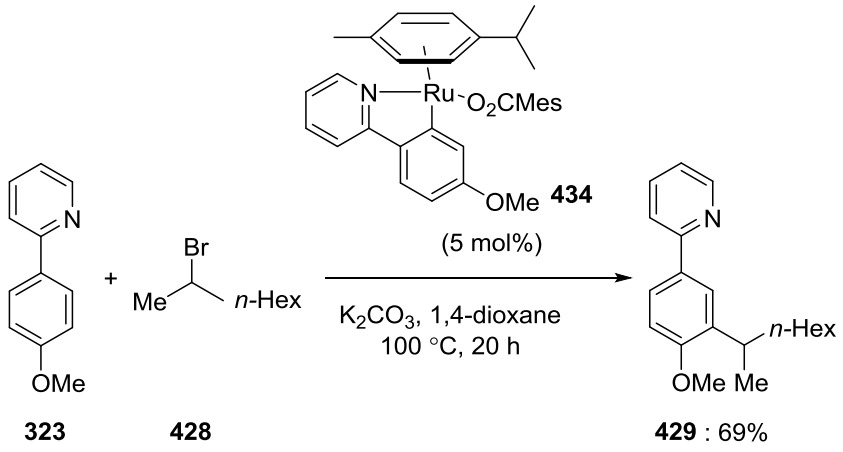


Scheme 175

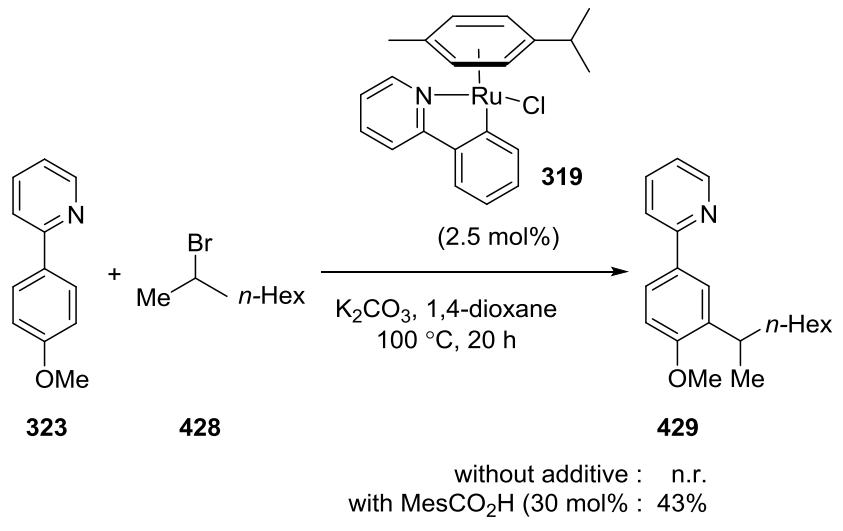


Scheme 176

Ackermann has also synthesised the well-defined ruthenium-substrate complex **434** and used it as the catalyst under the *meta*-alkylation conditions, and selectively delivered the *meta*-product **429** in a high yield (Scheme 177). Interestingly, the chlororuthenacycle **319** did not furnish any products in the absence of the additive; however, addition of catalytic amount of $MesCO_2H$ restored the catalytic activity (Scheme 178). In this regard, for Ackermann's *meta*-alkylation to function the carboxylate ligand $MesCO_2H$ must be present in the reaction, whereas the *meta*-sulfonation does not require any additional additives to work.

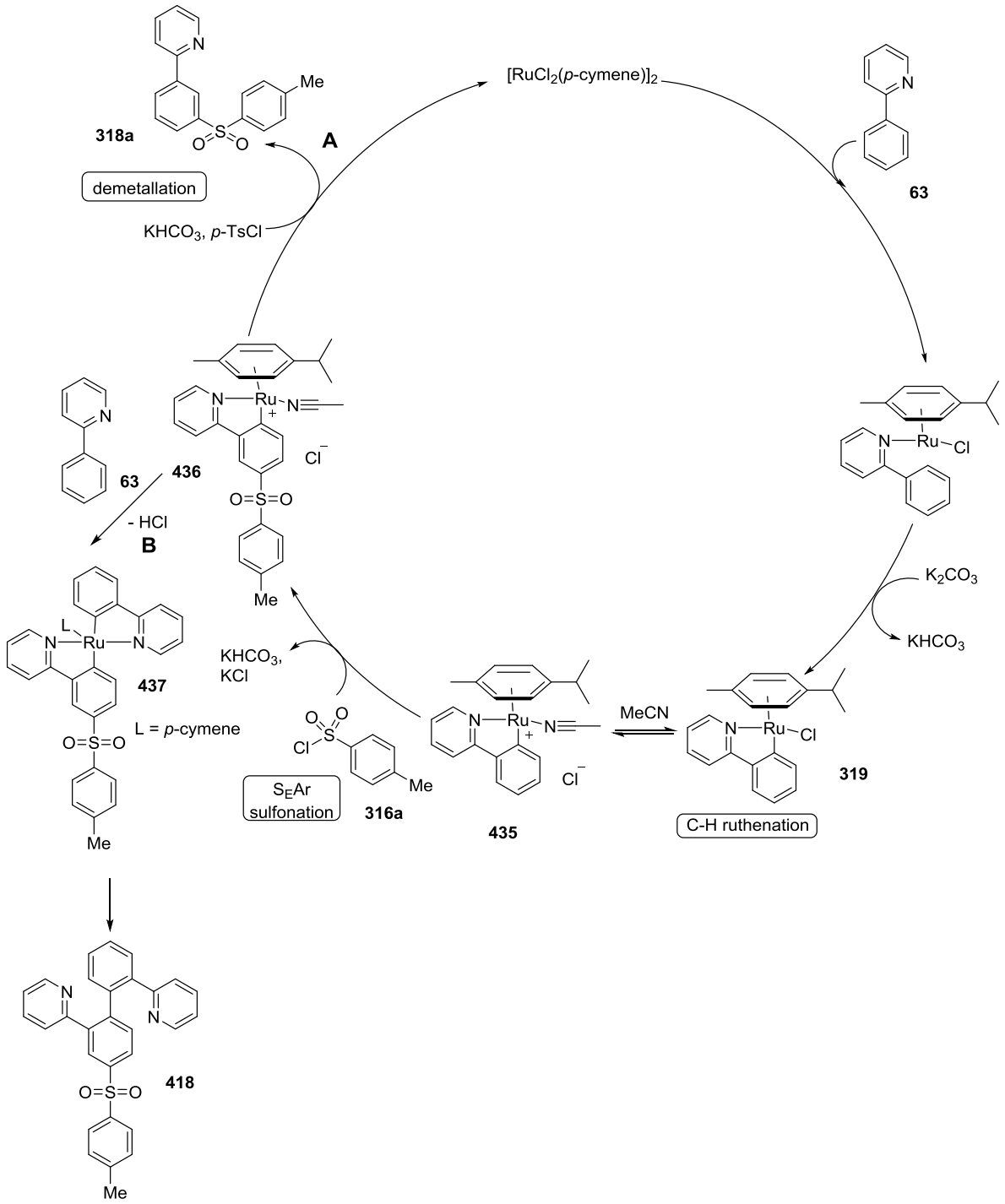


Scheme 177



Scheme 178

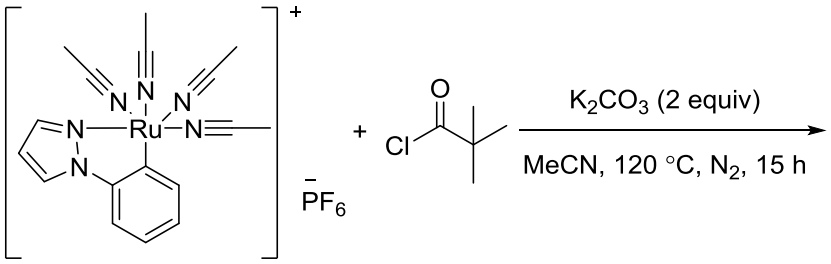
Based on the mechanistic studies presented herein and from previous work in the group as well as the work by Dixneuf and Ackermann and the DFT study on *meta*-sulfonation, a catalytic cycle is proposed (scheme 179). Firstly $[RuCl_2(p\text{-cymene})]_2$ reacts with 2-phenylpyridine **63** to form the cyclometallated ruthenacycle **319** *via* a concerted metallation-deprotonation mechanism (CMD) where the carbonate ligand is used in the deprotonation process.[13, 14] Complex **319** is in equilibrium with the solvated complex **435**, and this cyclometallacycle activates the susbtrate, where there is a *para*-directing effect from the Ru-C σ-bond for a S_EAr-type sulfonation with aryl sulfonyl chloride to give complex **436**. Then the sulfonated complex **436** undergoes proto-demetallation to provide the desired *meta*-sulfonated product **318a** and regenerates the active catalytic species. It is hypothesised that because of the high temperature, there would be a gradual accumulation of complex **411**, and once this complex is saturated in the reaction, the reaction becomes stagnant and the active catalytic species cannot be regenerated to form more products. In addition, it is also noteworthy that complex **436** can react further, and undergo oxidative addition with unreacted 2-phenylpyridine **63** to form species **437** and reductive elimination to give the heterodimer **418** as product.



Scheme 179

Having established a proposed catalytic cycle for *meta*-sulfonation, the next step is to understand the *ortho*-acylation reaction. As mentioned in chapter 3, reaction of 2-phenylpyridine with *ortho*-toluoyl chloride treated under the *meta*-sulfonation conditions gave no results, therefore it was of interest to attempt acylation with complex **413**, as phenylpyrazole was the best susbtrate for *ortho*-C-H acylation. Trimethylacetyl chloride **400** was chosen as the acylating reagent, because the ^{t}Bu signal can be easily identified in the ^{1}H NMR spectrum. Reaction of complex **413** with

trimethylacetyl chloride, 2 equivalents of K_2CO_3 and CD_3CN in a Young's tube was heated at 120 °C in an oil bath. After heating overnight, analysis of ^1H NMR spectra showed the disappearance of trimethylacetyl chloride, and there was no sign of the ^{t}Bu group present at all and H7 is missing in the spectrum (Figure 14). In addition, ^{13}C NMR spectrum revealed that all of the carbon signals are the same as the starting material complex **413** with the exception of carbon 7, which is missing in the spectra. Furthermore, the quaternary carbon on position 11 is still bonded to the ruthenium centre as the peak at 165.1 ppm is clearly observed in the spectra (Figure 16). 2D NMR experiments revealed that there are no protons attached to this *ortho* carbon. As no ^{t}Bu group is observed in the spectra, one possibility that the complex **438** is chlorinated on the *ortho* position with the ruthenacycle intact. Unfortunately, MS analysis did not conclusively confirm the presence of chlorine isotopes in the spectra. (Scheme 181)



413 **400** (3 equiv)

Scheme 180

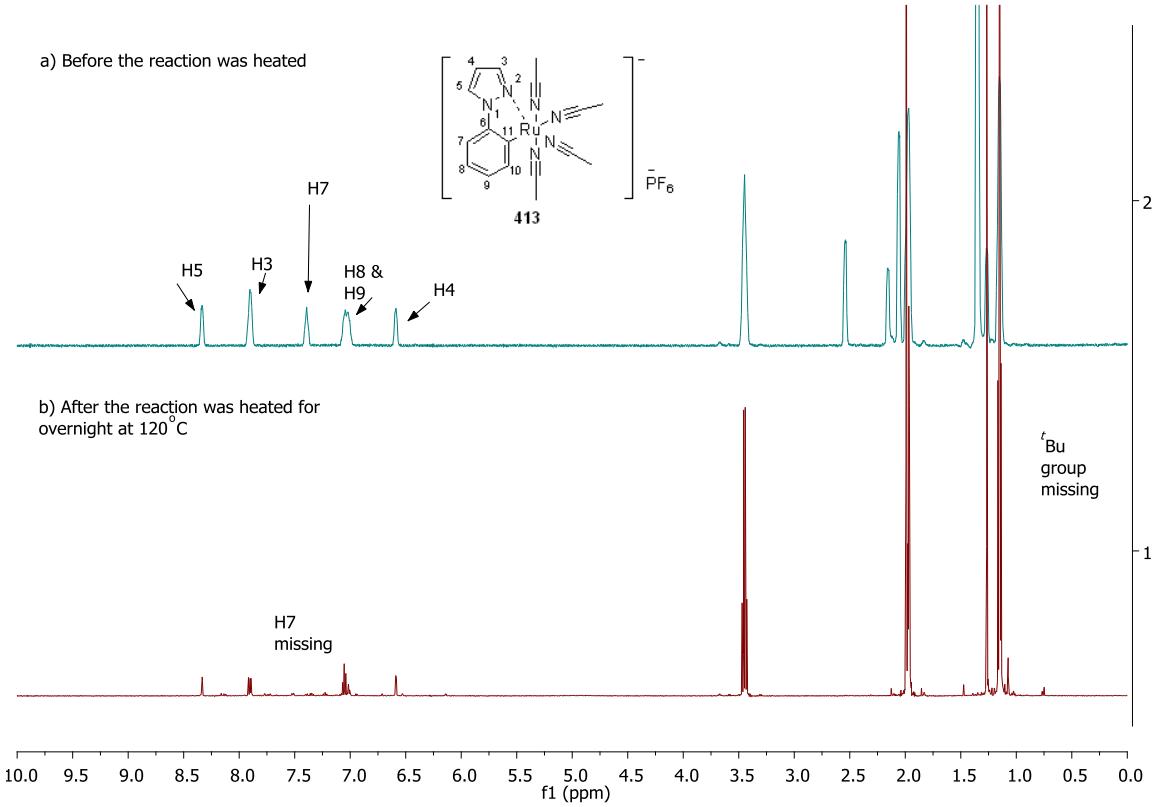


Figure 14

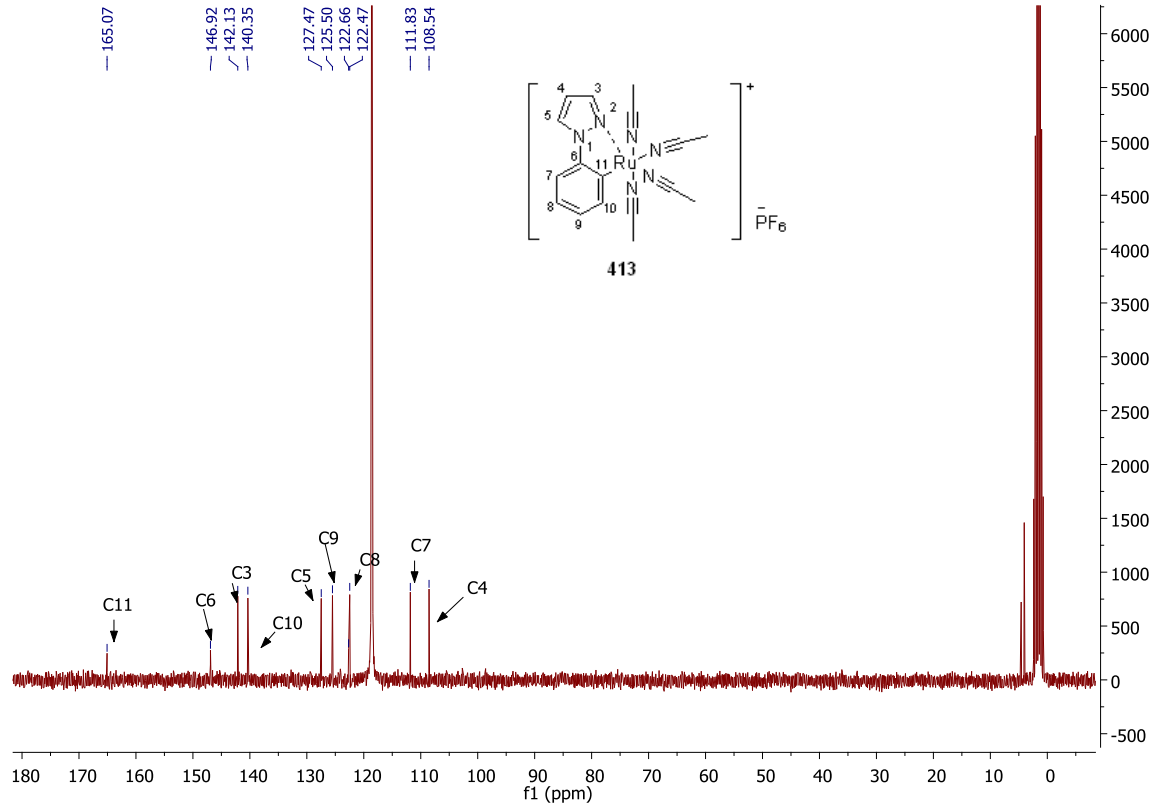


Figure 15

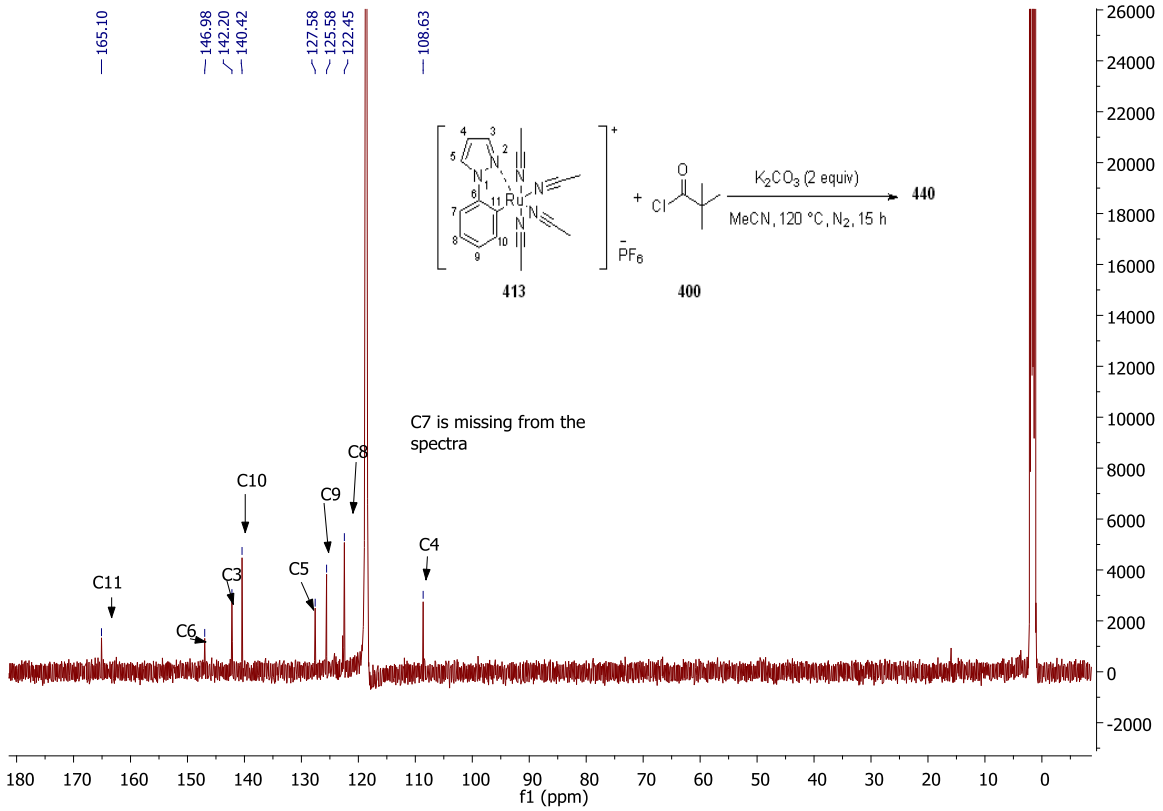
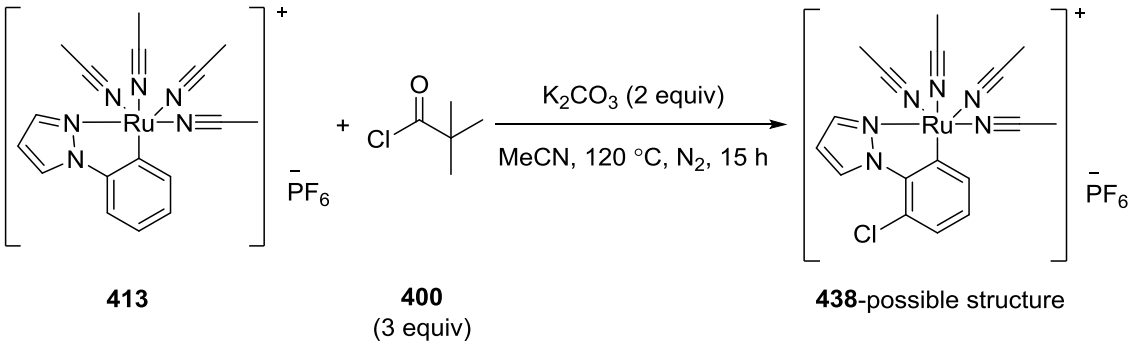


Figure 16



413 **400** (3 equiv) **438**-possible structure

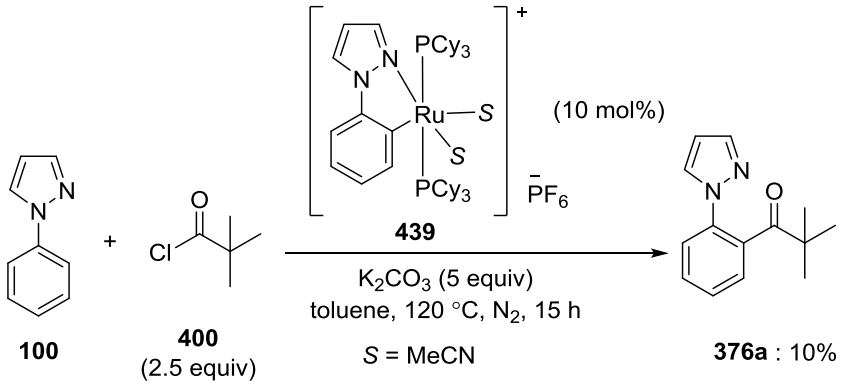
Scheme 181

This experimental finding shows that in the absence of phosphine ligands, the ruthenacycle does not undergo acylation. Intriguingly, under catalytic conditions, the *ortho*-chlorinated product has not been detected in the ^{1}H NMR spectra or TLC analysis. In addition, this finding clearly highlights an important factor of which the electrophile plays a major role on the regioselectivity of the product. Both the sulfonation and acylation were performed under the same reaction conditions except for the electrophile, one is a sulfonyl chloride and the other is an acid chloride,

yet the products obtained were of different regioselectivity. For *p*-TsCl the *meta*-sulfonated complex was observed, in contrast by switching the electrophile to trimethylacetyl chloride did not provide the *meta*-acylated product. From these findings, it suggests the electrophile appears to have a major influence on the mechanistic pathway.

4.1c. Mechanistic considerations of *ortho*-C-H acylation

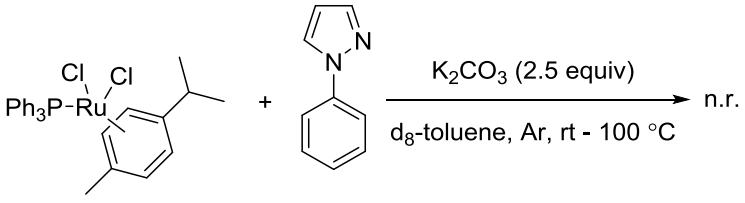
For the mechanistic study on *ortho*-acylation, phenylpyrazole was chosen as the substrate to study, as it was the most efficient substrate for *ortho*-C-H acylation. A member of the Frost group, Dr Patricia Marcé-Villa has kindly synthesised complex **439**, as there was only a small amount of the complex **439** available, it was decided to use this cyclometallated complex **439** as catalyst for C-H acylation. Phenylpyrazole **100** and trimethylacetyl chloride **400** were reacted in the presence of 10 mol% of complex **439** and 5 equivalents of K_2CO_3 in toluene at 120 °C (Scheme 182). After 15 hours of heating, only 10% conversion of **376a** was observed, this finding suggests that there was no catalyst turnover.



Scheme 182 ^{1}H NMR conversion

Firstly, the synthesis of complex **439** was attempted, however difficulties were accounted with the PCy_3 ligand, as it was prone to oxidation to form the oxidised PCy_3=O, therefore it was decided to replace the PCy_3 ligand with PPh_3. Since this ligand is much easier to handle and PPh_3 was compatible under the acylation conditions. Moreover, PPh_3 was present in the ruthenium(II) catalyst used in Kakiuchi's acylation conditions.[15]

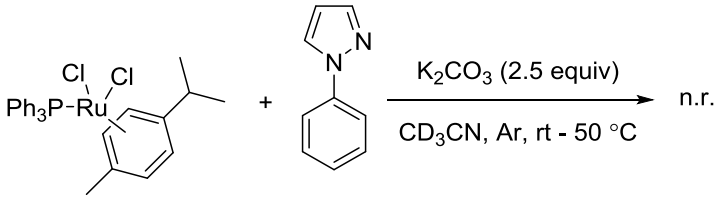
Complex **440** [$RuCl_2$(*p*-cymene)(PPh_3)] was synthesised following a literature procedure and complex **440** was used to understand the C-H activation step of the acylation catalytic cycle, to observe any difference in the C-H activation of the substrate in the presence of a phosphine ligand.[16] The C-H activation was performed in a Young's tube and the reaction was analysed by ^{1}H NMR spectroscopy. Complex **440** was treated with 1-phenylpyrazole **100** and 2.5 equivalents of K_2CO_3 in d_8-toluene, as the *ortho*-C-H acylation used toluene as the reaction solvent and checked the experiment every 5 to 10 minutes intervals and gradually increased the temperature to 100 °C (Scheme 183). It is noteworthy that at room temperature, the complex **440** is insoluble in d_8-toluene, it is only when the complex is heated at a high temperature, that the complex becomes soluble in the solvent. At 87 °C, no changes were observed in the ^{1}H NMR spectrum, however at 97 °C the *p*-cymene ligand starts to dissociate. After 4 hours of heating at 100 °C, there was no change to the phenylpyrazole substrate peaks, which suggests C-H activation has not taken place. The only noticeable changes observed were the dissociation of *p*-cymene and changes to the phosphorus peaks in the ^{31}P NMR spectra, but this can be attributed to the high temperature where the phosphine ligand is constantly interchanging between binding and unbinding to the ruthenium centre.



440 **100**

Scheme 183

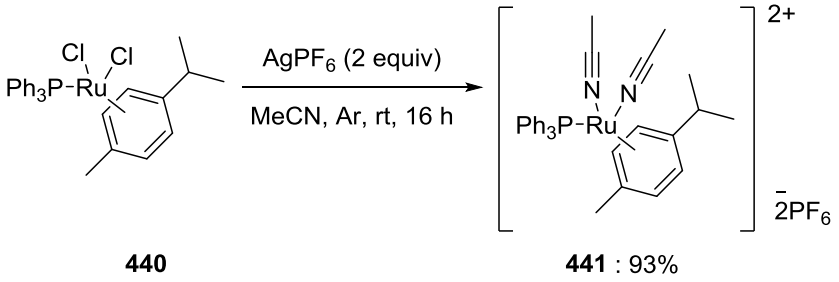
Due to the poor result, it was decided to attempt the same reaction in CD_3CN, as it is a polar solvent so the complex should be more soluble. Unfortunately, in this case C-H activation of phenylpyrazole **100** with complex **440** has also failed (Scheme 184).



440 **100**

Scheme 184

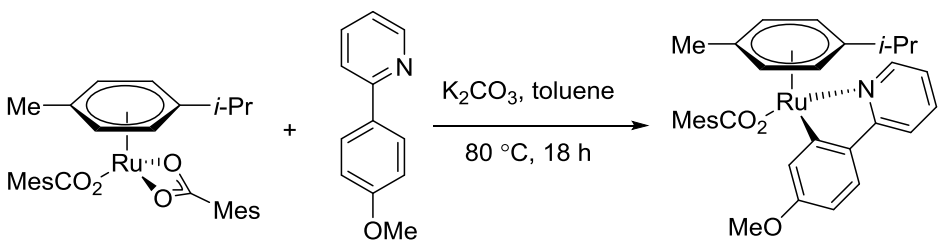
The C-H activation experiments were repeated again but at a higher temperature of 120 °C in both d_8-toluene and CD_3CN, however, no C-H activated phenylpyrazole ruthenacycle was observed. It is unsure why C-H activation would not take place, the only difference is the presence of the phosphine ligand, and it appears that the phosphine ligand is hindering the C-H activation step. Having encountered difficulties to form the C-H activated Ru-PPh_3 complex it was decided to ease the C-H ruthenation process by removing the chlorides with a silver salt to afford complex **441** (Scheme 185).



440 **441** : 93%

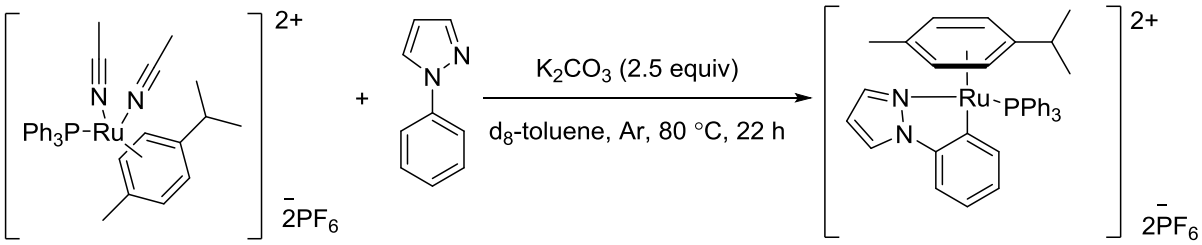
Scheme 185

Ackermann has reported forming a C-H activated complex at 80 °C in toluene as the reaction medium (Scheme 186), this shows that toluene can be used as the reaction medium to perform C-H activated cyclometallated complexes.[14] Therefore, it was decided to attempt C-H activation of phenylpyrazole with complex **441** and in the presence of 2.5 equivalents of K_2CO_3 at 80 °C in toluene. After 22 hours, some of the phenylpyrazole underwent cyclometallation to afford complex **442** with a low yield of 14% yield (Scheme 187). Although the yield is disappointingly low, nevertheless, it shows that a ruthenium-phosphine complex can undergo C-H activation with an aromatic substrate.



80 **323** **434** : 60%

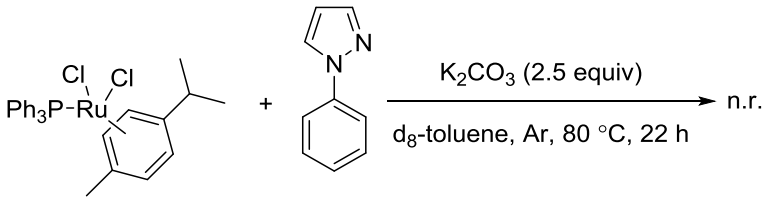
Scheme 186



441 **100** **442** : 14%

Scheme 187

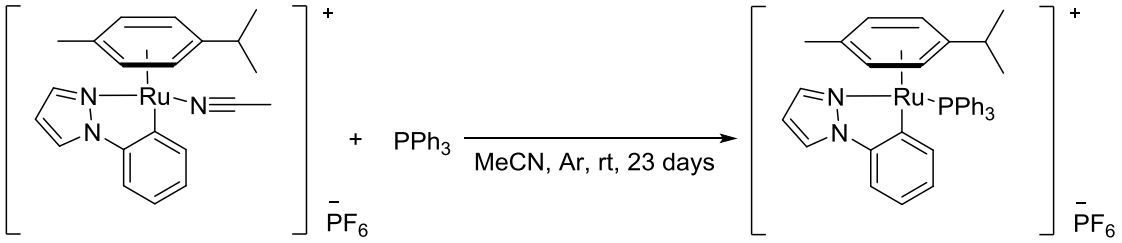
The same conditions were used for the chlorinated complex **440** to attempt C-H activation with phenylpyrazole and surprisingly the reaction failed (Scheme 188).



440 **100**

Scheme 188

An alternative method of synthesising the Ru-phosphine substrate complex is by reacting complex **412** with PPh_3 at room temperature to afford the desired complex **443** as product (Scheme 189).



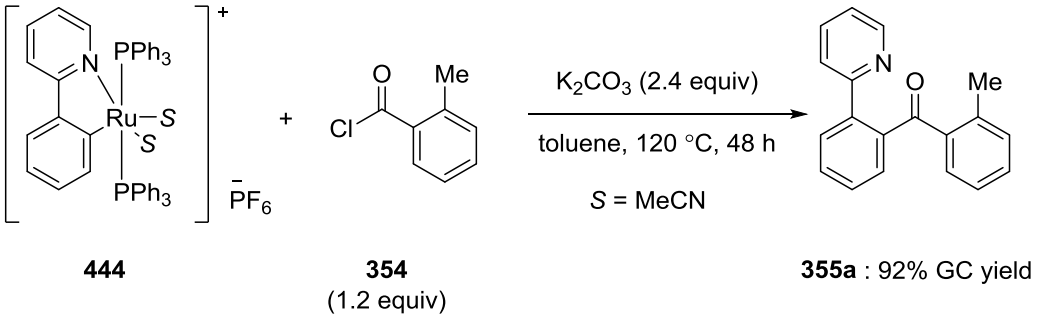
412 **443** : 7%

Scheme 189

From these C-H activation experiments, difficulties have been encountered to form the desired ruthenacycle, which suggests that for C-H bond cleavage to happen there is a certain energy barrier to overcome. As shown in Scheme 181, the C-H activated complex was made at 80 °C and it was heated for a long duration to obtain only a small amount of product **442**. This work is in

agreement with Dixneuf's study, as Dixneuf has also observed C-H activation of 2-phenylpyridine with a Ru complex is considerably slower in toluene compared to MeCN.[2]

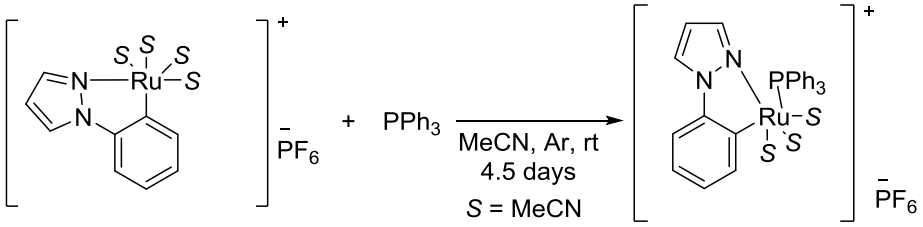
Before utilising the C-H activated complexes to perform C-H acylation, it was decided to synthesise another two complexes for comparison reasons. As Kakiuchi and co-workers have synthesised complex **444** and performed acylation with complex **444** to form the acylated product **355a** but with prolonged heating of 48 hours (Scheme 190).[15]



444 **354** (1.2 equiv) **355a** : 92% GC yield

Scheme 190

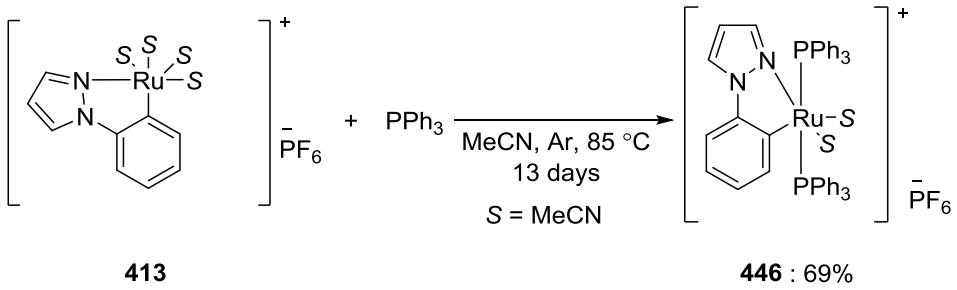
By synthesising both the mono and bisphosphinated complexes it can be used to compare with Kakiuchi's finding and in addition to provide mechanistic insights into the *ortho*-C-H acylation, whether one or two phosphine ligands are required to form the acylated products. Complex **413** was used as the starting material and it was reacted with PPh_3 in MeCN under an atmosphere of argon at room temperature for 4.5 days and gave the monophosphine complex **445** in 94% yield (Scheme 191).[17]



413 **445** : 94%

Scheme 191

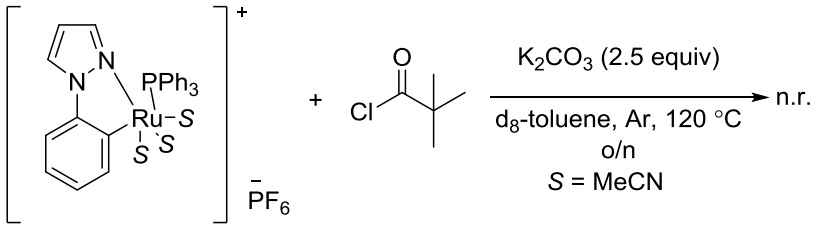
The bisphosphinated complex was synthesised by reacting complex **413** with PPh_3 in MeCN, sealed under an atmosphere of Ar and heated at 85 °C for 13 days to afford the desired complex **446** in 69% yield (Scheme 192).[17]



413 **446** : 69%

Scheme 192

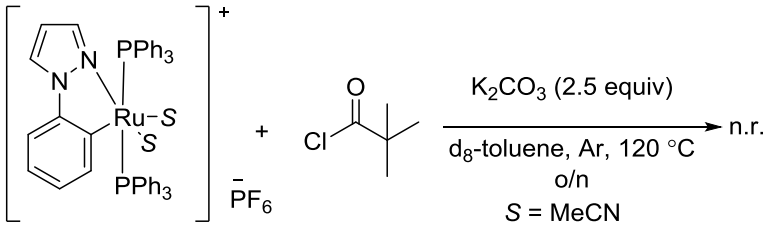
In a Young's tube with complex **445**, 2.5 equivalents of trimethylacetyl chloride **400** and K_2CO_3 in d_8-toluene and heated at 120 °C for overnight (Scheme 193). The reaction mixture formed a black precipitate and analysis of the experiment by ^1H NMR spectroscopy showed no sign of product, and it was decided to leave the reaction to heat for another 24 hours. Unfortunately, a total of 48 hours of heating showed no product formed. The same reaction was performed in a larger scale in a Schlenk tube, after 1 hour of heating the reaction turned black and after 48 hours of heating no product was found in the ^1H NMR spectrum.



445 **400** (2.5 equiv)

Scheme 193

Due to the poor result with **445**, it was expected that **446** would likely to react and provide the acylated product as Kakiuchi have used the 2-phenylpyridine complex **444** to perform the acylation reaction. After overnight heating, a black precipitate was formed and analysis of the ^1H NMR spectrum showed no product was formed in the reaction (Scheme 194).

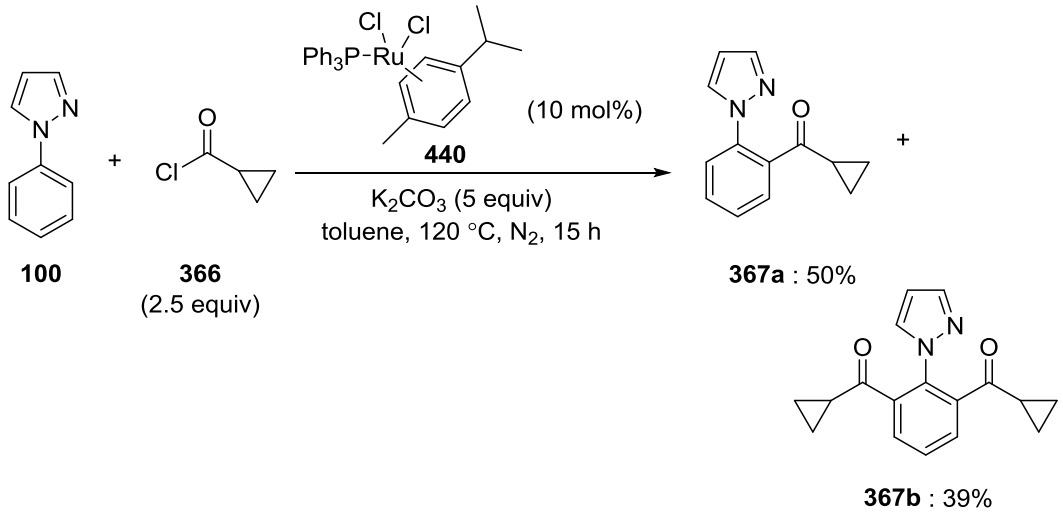


446 **400** 2.5 equiv

Scheme 194

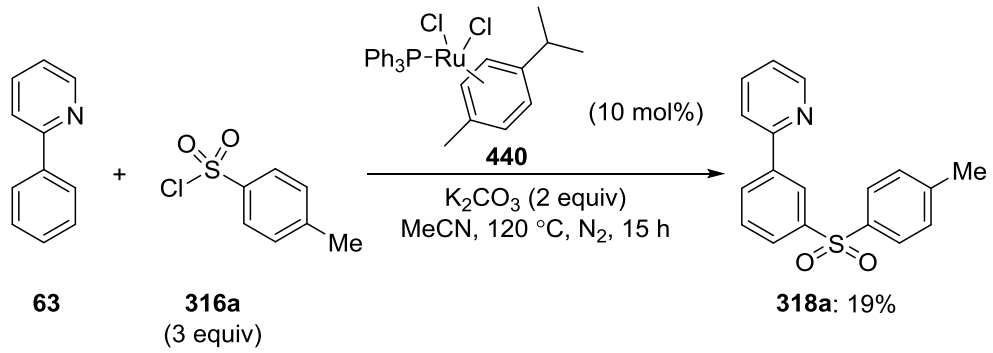
The reason behind the failure for the acylation of complex **445** and **446** was that the acid chloride used was found to have some impurity in the reagent. Unfortunately, this realisation was too late, as due to time constraint was unable to purify the acid chloride in time to repeat the experiments.

As mentioned earlier complex **440** failed to perform C-H activation with phenylpyrazole. Despite that, it was decided to attempt to use complex **440** as a catalyst, substituting $[RuCl_2(p\text{-cymene})]_2$ with complex **440** to perform C-H acylation. Phenylpyrazole **100** and cyclopropanecarbonyl chloride **366** reacted under the *ortho*-acylation conditions in the presence of 10 mol% of complex **440** and 5 equivalents of K_2CO_3 in toluene at 120 °C for 15 hours. Analysis of the crude ^{1}H NMR spectrum gave the mono and bis-acylated products **367a** and **367b** in 50 and 39% conversions respectively (Scheme 195). This finding is comparable to the results observed in Chapter 3, which suggests that one PPh_3 ligand is sufficient to perform the *ortho*-acylation. More importantly, it shows though this complex failed to cyclometallate with phenylpyrazole in a stoichiometric reaction, however, it has demonstrated that it can be used as a catalyst in *ortho* C-H acylation and there is catalyst turnover. Contrastingly, complex **439** containing two PCy_3 ligands reacted under acylation conditions but with no catalyst turnover, this indicates that the *p*-cymene ligand could be crucial in the catalytic cycle for catalyst regeneration.



Scheme 195 ^{1}H NMR conversion

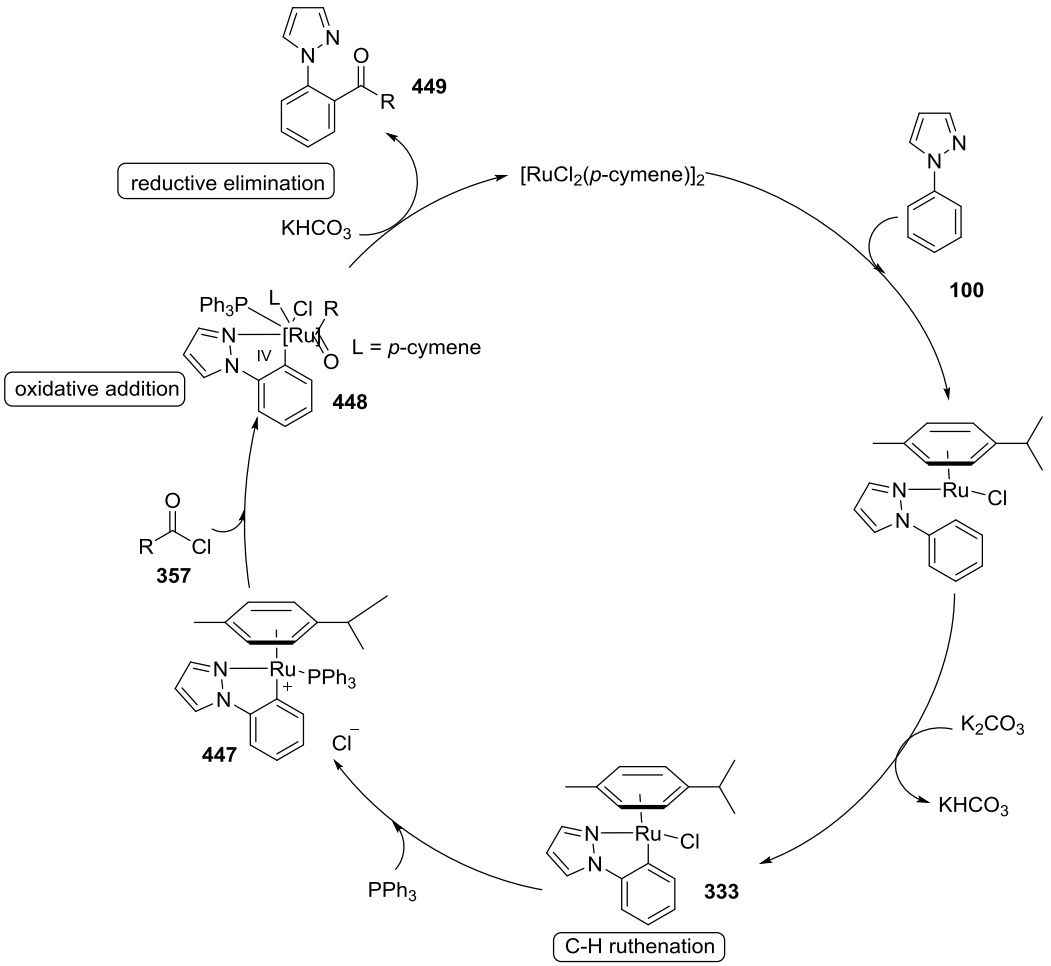
Complex **440** was also used as the catalyst to attempt to perform *meta*-sulfonation. Treatment of 2-phenylpyridine **63** with *p*-TsCl **316a** in the presence of complex **440** and 2 equivalents of K_2CO_3 in MeCN and was heated at 120 °C. After heating for 15 hours, crude ^{1}H NMR spectrum revealed that there was 19% conversion of the *meta*-sulfonated product **318a** present (Scheme 196). This result shows that complex **440** can also be used as the catalyst for *meta*-sulfonation. However, complex **440** is not as efficient as $[RuCl_2(p\text{-cymene})]_2$ for catalysing the *meta*-sulfonation reaction, as the isolated yield obtained is 54% yield with the $[RuCl_2(p\text{-cymene})_]_2$ complex.



Scheme 196 ^{1}H NMR conversion

Although the detailed mechanism is still unclear, however, combining the mechanistic study presented herein and the work by Dixneuf and Kakiuchi for the basis of our proposed catalytic cycle for *ortho*-acylation (Scheme 197). Firstly, $[RuCl_2(p\text{-cymene})]_2$ reacts with 1-phenylpyrazole to give the five-membered ruthenacycle **333** *via* a CMD mechanism facilitated by K_2CO_3. Ligand

exchange to give the monophosphine complex **448**. The electron rich complex **448** attacks the acid chloride to undergo oxidative addition to form Ru(IV) species **449**, followed by reductive elimination to give the acylated product **450**. In chapter 3, it was mentioned that the sterically hindered acid chlorides such as trimethylacetyl chloride and adamantanecarbonyl chloride provided the best yields; this was due to a steric acceleration effect in the reductive elimination step.



Scheme 197

4.1.2. Conclusions

In conclusion, stoichiometric experiments on *meta*-sulfonation have shown that the sulfone is substituted *para* to the Ru-C σ-bond, which clearly indicates the Ru-C_{aryl} σ-bond acts as a directing group to perform the S_EAr reaction. Furthermore, it appears that the extra addition of *p*-TsCl is necessary for demetallation to occur, to give the *meta*-sulfonated product. Interestingly, replacing the electrophile with an acid chloride does not give a *meta*-acylated product instead, a

chlorinated substrate-Ru complex is observed, although further elucidation such as X-ray crystallography is needed to verify the structure.

Stoichiometric experiments on the C-H activation of Ru-phosphine complexes with 1-phenylpyrazole was attempted and have shown little success in affording the C-H activated complex, which suggests that C-H bond cleavage is a difficult process in the presence of phosphine ligands. Complex **440** has demonstrated it is a viable catalyst for *ortho*-acylation and *meta*-sulfonation, more importantly, this experimental finding has revealed that acylation can operate with only one PPh_3 ligand.

Finally, two catalytic cycles were proposed for *meta*-sulfonation and *ortho*-acylation. It is believed that the *meta*-selectivity is the result of an inductive effect, which directs the electrophile to *para* to the Ru-C_{aryl} σ-bond to perform the S_EAr mechanism. In contrast, *ortho*-acylated products are obtained because the acylation follows a different mechanistic pathway, where the acid chloride undergoes oxidative addition followed by reductive elimination.

4.2. References

1. X. Zhao, E. Dimitrijevic and V. M. Dong, *J. Am. Chem. Soc.*, 2009, **131**, 3466-3467.
2. E. F. Flegeau, C. Bruneau, P. H. Dixneuf and A. Jutand, *J. Am. Chem. Soc.*, 2011, **133**, 10161-10170.
3. I. Fabre, N. von Wolff, G. Le Duc, E. F. Flegeau, C. Bruneau, P. H. Dixneuf and A. Jutand, *Chem. Eur. J.*, 2013, **19**, 7595-7604.
4. B. Li, T. Roisnel, C. Darcel and P. H. Dixneuf, *Dalton Trans.*, 2012, **41**, 10934-10937.
5. A. M. Clark, C. E. F. Rickard, W. R. Roper and L. J. Wright, *Organometallics*, 1998, **17**, 4535-4537.
6. A. M. Clark, C. E. F. Rickard, W. R. Roper and L. J. Wright, *Organometallics*, 1999, **18**, 2813-2820.
7. M. Gagliardo, D. J. M. Snelders, P. A. Chase, R. J. M. K. Gebbink, G. R. M. van Klink and G. van Koten, *Angew. Chem. Int. Ed.*, 2007, **46**, 8558-8573.
8. M. A. Bennett and A. K. Smith, *J. Chem. Soc. Dalton Trans.*, 1974, 233-241.
9. O. Saidi, J. Marafie, A. E. W. Ledger, P. M. Liu, M. F. Mahon, G. Kociok-Kohn, M. K. Whittlesey and C. G. Frost, *J. Am. Chem. Soc.*, 2011, **133**, 19298-19301.
10. D. J. Liu, H. Z. Yu and Y. Fu, *Acta Chim. Sinica*, 2013, **71**, 1385-1395.
11. N. Hofmann and L. Ackermann, *J. Am. Chem. Soc.*, 2013, **135**, 5877-5884.
12. L. Ackermann, P. Novak, R. Vicente and N. Hofmann, *Angew. Chem. Int. Ed.*, 2009, **48**, 6045-6048.
13. I. Ozdemir, S. Demir, B. Cetinkaya, C. Gourlaouen, F. Maseras, C. Bruneau and P. H. Dixneuf, *J. Am. Chem. Soc.*, 2008, **130**, 1156-1157.
14. L. Ackermann, R. Vicente, H. K. Potukuchi and V. Pirovano, *Org. Lett.*, 2010, **12**, 5032-5035.

15. T. Kochi, A. Tazawa, K. Honda and F. Kakiuchi, *Chem. Lett.*, 2011, **40**, 1018-1020.
16. E. E. Joslin, C. L. McMullin, T. B. Gunnoe, T. R. Cundari, M. Sabat and W. H. Myers, *Inorg. Chem.*, 2012, **51**, 4791-4801.
17. L. Leyva, C. Sirlin, L. Rubio, C. Franco, R. Le Lagadec, J. Spencer, P. Bischoff, C. Gaiddon, J. P. Loeffler and M. Pfeffer, *Eur. J. Inorg. Chem.*, 2007, 3055-3066.

Grind away, moisten and mash up thy paste,

Pound at thy powder, – I am not in haste!

Better sit thus, and observe thy strange things,

Than go where men wait and dance at the King's

That in the mortar– you call it a gum?

Ah, the brave tree whence such gold oozings come!

And yonder soft phial, the exquisite blue,

Sure to taste sweetly,–is that poison too?

Verses III & IV of the poem "The Laboratory" – Ancien Régime by Robert Browning (1844)

Chapter 5. Experimental

5.1. General Considerations

All reagents were commercially available and purchased from Sigma-Aldrich Company Ltd, Acros Organics, Alfa Aesar, Fisher Scientific, Johnson Matthey, Strem Chemical and Frontier Scientific chemical companies, and were used without further purification unless specified. Solvents were dried and obtained by passing through anhydrous alumina columns using an Innovative Technology Inc. PS-400-7 solvent purification system. Cyclopropanecarbonyl chloride, cyclopentanecarbonyl chloride, cyclohexanecarbonyl chloride and *o*-toluoyl chloride were distilled and dried over 3 Å molecular sieves. Potassium carbonate was heated in an oven at 200 °C prior to use for the work on C-H acylation. 'Petrol' refers to the fraction of petroleum ether boiling in the range of 40 – 60 °C. Acetone was dried over potassium carbonate. All air-sensitive reactions were carried out under nitrogen or argon atmospheres using standard Schlenck line techniques. Analytical thin layer chromatography was performed using commercially available backed plates coated with Merck G/UV254 neutral silica. Plates were visualised under UV light (at 254 nm). Silica flash chromatography was performed on chromatography grade, silica 60 Å particle size 200 – 400 micron mesh particle size from Sigma-Aldrich. Alumina flash chromatography was performed on neutral Brockmann I chromatography grade, aluminium oxide 60 Å particle size 50 – 200 micron from Acros Organics.

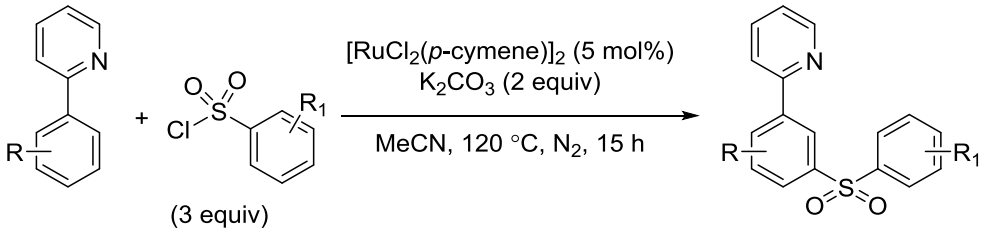
NMR spectra were recorded on Bruker AV 250, AV 300, AV 400 or AV 500 spectrometers at 298 K. Chemical shifts (δ) are expressed in parts per million (ppm). ^{1}H NMR spectra were referenced internally to residual protic solvent signal at (^{1}H 7.26 ppm, s and ^{13}C 77.0 ppm, t for $CDCl_3$), (^{1}H 1.94 ppm, quint. or 2.13 ppm, s and ^{13}C 118.26 ppm, s or 1.32 ppm, hept. for CD_3CN) (^{1}H 7.00 ppm, s and ^{13}C 137.86 ppm for d_8-toluene), ^{19}F NMR spectra were referenced to 100% $CFCl_3$ (0.00 ppm) and ^{31}P NMR spectra were referenced to 85% H_3PO_4 (0.00 ppm). Assignments were supported by ^{1}H, ^{13}C and PENDANT ^{13}C NMR and homo- and heteronuclear, one- and two-dimensional experiments as appropriate. The multiplicities of the spectrometric data are presented in the following manner: singlet (s), broad singlet (br s), doublet (d), apparent doublet (app d), doublet of doublets (dd), doublet of triplets (dt), doublet of doublet of doublets (ddd), heptet (hept), triplet (t), apparent triplet (app t), triplet of doublets (td), doublet doublet doublet

of doublets (dddd), triplet of triplets (tt), quartet (q), quintet (quint.), apparent quintet (app quint.) and multiplet (m). Coupling constants, (*J*) are expressed in Hertz (Hz).

IR spectra were recorded on Perkin-Elmer 1600 FT IR spectrometer with only selected absorbances quoted as ν in cm^{-1}. All capillary melting points were recorded using a Bibby Scientific Melting point apparatus Stuart SMP10 digital. The mass spectra were run on a microTOF electrospray time of flight (ESI-µTOF) coupled to an Agilent 1200 LC system.

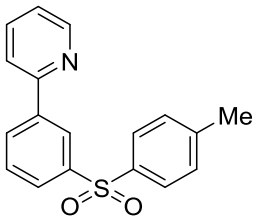
5.2. Chapter 2 Experimental Procedures

5.2.1. General Procedure I[1]



To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (30 mg, 0.05 mmol) and dry acetonitrile (3 mL) and the solution was stirred under N_2. To this was added 2-phenylpyridine derivatives (1.0 mmol), K_2CO_3 (0.27 g, 2.0 mmol) and the sulfonylchloride derivatives (3.0 mmol) and the reaction mixture was purged under N_2 then heated at 120 °C with stirring. After 15 h, the reaction mixture was cooled to rt and the crude mixture was quenched with water (1 mL) and the organic material was extracted with dichloromethane (6 × 20 mL). The organics were dried over $MgSO_4$, filtered and the solvent was removed *in vacuo*. The product is then purified by silica flash column chromatography with the appropriate eluent.

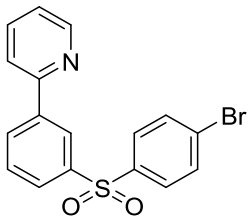
2-(3-Tosylphenyl)pyridine (318a)



Following General Procedure I, 2-phenylpyridne (140 µL, 1.0 mmol) and *p*-toluenesulfonyl chloride (0.58 g, 3.0 mmol) in dry MeCN (3 mL) were reacted, and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give a white solid (149 mg, 49%);

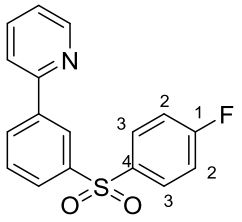
mpt. 124 – 126 °C; ν_{max} (neat) / cm^{-1}; 3066, 1585, 1467, 1432, 1409; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.72 – 8.67 (1H, m, Ar*H*), 8.54 (1H, t, *J* = 1.7 Hz, Ar*H*), 8.22 (1H, ddd, *J* = 7.8, 1.7, 1.2 Hz, Ar*H*), 7.95 (1H, ddd, *J* = 7.8, 1.7, 1.2 Hz, Ar*H*), 7.89 – 7.84 (2H, m, Ar*H*), 7.82 – 7.72 (2H, m, Ar*H*), 7.59 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.32 – 7.24 (3H, m, Ar*H*), 2.38 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.4 (Ar*C*N), 150.0 (Ar*C*HN), 144.4 (Ar*C*SO_2), 142.7 (Ar*C*Me), 140.8 (Ar*C*SO_2), 138.7 (Ar*C*), 137.2 (Ar*C*H), 131.5 (Ar*C*H), 130.1 (2 × Ar*C*H), 129.9 (Ar*C*H), 127.9 (3 × Ar*C*H), 125.9 (Ar*C*H), 123.1 (Ar*C*H), 120.8 (Ar*C*H), 21.7 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{18}H_{15}NO_2S$; $[M+H]^+$: 310.0902, found: 310.0890.

2-(3-((4-Bromophenyl)sulfonyl)phenyl)pyridine(318b)



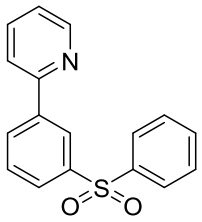
Following General Procedure I, 2-phenylpyridne (140 µL, 1.0 mmol) and 4-bromobenzenesulfonyl chloride (0.75 g, 3.0 mmol) in dry MeCN (3 mL)were reacted and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (84 mg, 23%); mpt. 194 – 200 °C; ν_{max} (neat) / cm^{-1}; 3083, 2365, 1586, 1569, 1459, 1407; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.69 (1H, dt, *J* = 4.8, 1.2 Hz, Ar*H*), 8.56 (1H, t, *J* = 1.7 Hz, Ar*H*), 8.23 (1H, dt, *J* = 8.1, 1.4 Hz, Ar*H*), 7.95 (1H, ddd, *J* = 8.1, 1.4, 0.3 Hz, Ar*H*), 7.87 – 7.80 (2H, m, Ar*H*), 7.80 – 7.72 (2H, m, Ar*H*), 7.65 – 7.58 (3H, m, Ar*H*), 7.31 – 7.25 (1H, m, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.1 (Ar*C*N), 150.0 (Ar*C*HN), 141.8 (Ar*C*), 141.0 (Ar*C*), 140.6 (Ar*C*), 137.2 (Ar*C*H), 132.7 (2 × Ar*C*H), 131.9 (Ar*C*H), 130.0 (Ar*C*H), 129.3 (2 × Ar*C*H), 128.6 (Ar*C*Br), 127.9 (Ar*C*H), 126.1 (Ar*C*H), 123.2 (Ar*C*H), 120.8 (Ar*C*H); HRMS (ESI µTOF) m/z calcd for $C_{17}H_{12}{}^{79}BrNO_2S$ $[M+H]^+$: 373.9850, found: 373.9843.

2-(3-((4-Fluorophenyl)sulfonyl)phenyl)pyridine (318c)



Following General Procedure I, 2-phenylpyridne (140 µL, 1.0 mmol) and 4-fluorobenzenesulfonyl chloride (0.58 g, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (192 mg, 62%); mpt. 130 – 133 °C; ν_{max} (neat) / cm^{-1}; 3071, 1586, 1492, 1467, 1431; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.66 (1H, d, *J* = 4.8 Hz, Ar*H*), 8.57 (1H, t, *J* = 1.7 Hz, Ar*H*), 8.20 (1H, dt, *J* = 7.8, 1.1 Hz, Ar*H*), 8.02 – 7.96 (2H, m, Ar*H*), 7.94 (1H, dt, *J* = 7.8, 1.1 Hz, Ar*H*), 7.78 – 7.70 (2H, m, Ar*H*), 7.58 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.25 (1H, ddd, *J* = 6.0, 4.8, 2.5 Hz, Ar*H*), 7.18 – 7.09 (2H, m, Ar*H*).; ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.5 (d, *J* = 256.0 Hz, ArC_1F), 155.0 (Ar*C*N), 149.9 (Ar*C*HN), 142.1 (Ar*C*), 140.9 (Ar*C*), 137.6 (d, *J* = 3.2 Hz, ArC_4), 137.1 (Ar*C*H), 131.6 (Ar*C*H), 130.6 (d, *J* = 9.6 Hz, 2 × ArC_3H), 129.9 (Ar*C*H), 127.8 (Ar*C*H), 125.9 (Ar*C*H), 123.1 (Ar*C*H), 120.7 (Ar*C*H), 116.7 (d, *J* = 22.7 Hz, 2 × ArC_2H); ^{19}F NMR (376 MHz, $CDCl_3$): -103.9 – -104.0 (m, Ar*F*); HRMS (ESI µTOF) m/z calcd for $C_{17}H_{12}FNO_2S$ $[M+H]^+$: 314.0651, found: 314.0637.

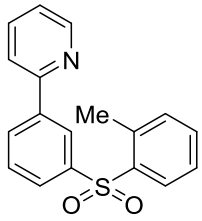
2-(3-(Phenylsulfonyl)phenyl)pyridine (318d)



Following General Procedure I, 2-phenylpyridine (140 µL, 1.0 mmol) and benzenesulfonyl chloride (380 µL, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a yellow solid (139 mg, 48%); mpt. 124 – 126 °C; ν_{max} (neat) / cm^{-1}; 1644, 1585, 1446; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.68 (1H, d, *J* = 4.6 Hz, Ar*H*), 8.61 (1H, s, Ar*H*), 8.22 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.99 (3H, m, Ar*H*), 7.81 – 7.72 (2H, m, Ar*H*), 7.60 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.56 – 7.44 (3H, m, Ar*H*), 7.31 – 7.24 (1H, m, Ar*H*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.9 (Ar*C*N), 149.7 (Ar*C*HN), 142.2 (Ar*C*), 141.4 (Ar*C*), 140.5 (Ar*C*), 137.2 (Ar*C*H), 133.3 (Ar*C*H), 131.5 (Ar*C*H), 129.8 (Ar*C*H), 129.3 (2 × Ar*C*H), 127.9

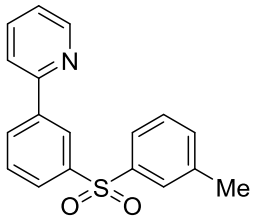
(Ar*C*H), 127.6 (2 × Ar*C*H), 125.9 (Ar*C*H), 123.1 (Ar*C*H), 120.7 (Ar*C*H); HRMS (ESI μTOF) m/z calcd for $C_{17}H_{13}NO_2S$ $[M+H]^+$: 296.0745, found: 296.0738.

2-(3-(*o*-Tolylsulfonyl)phenyl)pyridine (318e)



Following General Procedure I, 2-phenylpyrdine (140 μL, 1.0 mmol) and *o*-toluenesulfonyl chloride (430 μL, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a yellow oil (86 mg, 28%); ν_{max} (neat) / cm^{-1}; 3063, 1587, 1565, 1459, 1433, 1408; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.67 (1H, d, *J* = 4.7 Hz, Ar*H*), 8.48 (1H, t, *J* = 1.8 Hz, Ar*H*), 8.25 – 8.22 (2H, m, Ar*H*), 7.86 (1H, ddd, *J* = 7.7, 1.8, 1.2 Hz, Ar*H*), 7.76 (1H, td, *J* = 7.7, 1.8 Hz, Ar*H*), 7.72 (1H, d, *J* = 7.7 Hz, Ar*H*), 7.58 (1H, t, *J* = 7.7 Hz, Ar*H*), 7.45 (1H, td, *J* = 7.7, 1.2 Hz, Ar*H*), 7.39 – 7.36 (1H, m, Ar*H*), 7.28 – 7.24 (1H, m, Ar*H*), 7.20 (1H, d, *J* = 7.5 Hz, Ar*H*), 2.46 (3H, s, ArCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.1 (Ar*C*N), 149.8 (Ar*C*HN), 141.9 (Ar*C*), 140.4 (Ar*C*), 138.7 (Ar*C*), 138.0 (Ar*C*), 137.3 (Ar*C*H), 133.8 (Ar*C*H), 132.8 (Ar*C*H), 131.5 (Ar*C*H), 129.6 (Ar*C*H), 129.5 (Ar*C*H), 128.0 (Ar*C*H), 126.6 (Ar*C*H), 126.0 (Ar*C*H), 123.2 (Ar*C*H), 120.8 (Ar*C*H), 20.3 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{15}NO_2S$ $[M+H]^+$: 310.0902, found: 310.0894.

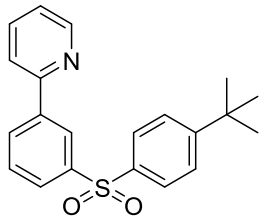
2-(3-(*m*-Tolylsulfonyl)phenyl)pyridine (318f)



Following General Procedure I, 2-phenylpyridine (140 μL, 1.0 mmol) and *m*-toluenesulfonyl chloride (430 μL, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a yellow oil (150 mg, 50%); ν_{max} (neat) / cm^{-1}; 1585, 1460; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.65 (1H, m, Ar*H*), 8.56 (1H, t, *J* = 1.8 Hz, Ar*H*), 8.20 – 8.17 (1H, m, Ar*H*), 7.95 (1H, ddd, *J* = 7.8, 1.8, 1.0 Hz, Ar*H*),

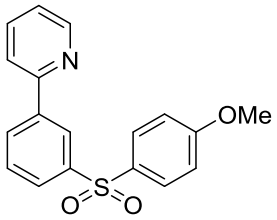
7.79 – 7.70 (4H, m, Ar*H*), 7.56 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.36 – 7.32 (1H, m, Ar*H*), 7.30 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.24 (1H, ddd, *J* = 6.6, 4.8, 1.8 Hz, Ar*H*), 2.33 (3H, s, ArCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.0 (Ar*C*N), 149.7 (Ar*C*HN), 142.3 (Ar*C*), 141.3 (Ar*C*), 140.5 (Ar*C*), 139.6 (Ar*C*), 137.2 (Ar*C*H), 134.1 (Ar*C*H), 131.5 (Ar*C*H), 129.8 (Ar*C*H), 129.2 (Ar*C*H), 127.9 (2 × Ar*C*H), 125.9 (Ar*C*H), 124.8 (Ar*C*H), 123.1 (Ar*C*H), 120.8 (Ar*C*H), 21.3 (ArCH_3); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{15}NO_2S$ $[M+H]^+$: 310.0902, found: 310.0896.

2-(3-((4-(*tert*-Butyl)phenyl)sulfonyl)phenyl)pyridine (318g)



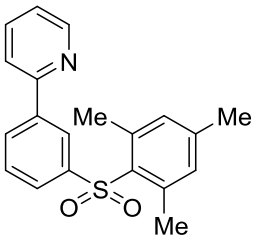
Following General Procedure I, 2-phenylpyrdine (140 μL, 0.98 mmol) and 4-*tert*-butylbenzenesulfonyl chloride (0.6972 g, 3.00 mmol) in dry MeCN (3 mL) were reacted using general procedure I and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a white solid (187 mg, 54%); mpt. 150 – 154 °C; ν_{max} (neat) / cm^{-1}; 3071, 1586, 1459; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.64 (1H, dt, *J* = 5.0, 1.4 Hz, Ar*H*), 8.58 (app t, *J* = 1.7 Hz, 1*H*), 8.17 (1H, ddd, *J* = 7.8, 1.7, 1.2 Hz, Ar*H*), 7.96 (1H, ddd, *J* = 7.8, 1.7, 1.2 Hz, Ar*H*), 7.92 – 7.87 (2H, m, Ar*H*), 7.73 – 7.71 (1H, m, Ar*H*), 7.71 (1H, d, *J* = 1.2 Hz, Ar*H*), 7.55 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.49 – 7.44 (2H, m, Ar*H*), 7.21 (1H, ddd, *J* = 5.0, 3.3, 1.7 Hz, Ar*H*), 1.23 (9H, s, C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 157.1 (Ar*C*), 155.1 (Ar*C*N), 149.8 (Ar*C*HN), 142.5 (Ar*C*), 140.6 (Ar*C*), 138.4 (Ar*C*), 137.0 (Ar*C*H), 131.3 (Ar*C*H), 129.7 (Ar*C*H), 127.8 (Ar*C*H), 127.5 (2 × Ar*C*H), 126.3 (2 × Ar*C*H), 125.8 (Ar*C*H), 123.0 (Ar*C*H), 120.6 (Ar*C*H), 35.1 (*C*(CH_3)$_3$), 30.9 (C(*C*H_3)$_3$); HRMS (ESI μTOF) m/z calcd for $C_{21}H_{21}NO_2S$ $[M+H]^+$: 352.1371, found 352.1382.

2-(3-((4-Methoxyphenyl)sulfonyl)phenyl)pyridine (318h)



Following General Procedure I, 2-phenylpyrdine (140 µL, 1.0 mmol) and 4-methoxybenzenesulfonyl chloride (0.61 g, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (193 mg, 61%); ν_{max} (neat) / cm^{-1}; 3096, 3069, 3016, 2840, 1588, 1574, 1561, 1498, 1471, 1460, 1431, 1413; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.66 – 8.62 (1H, m, Ar*H*), 8.54 (1H, t, *J* = 1.7 Hz, Ar*H*), 8.15 (1H, ddd, *J* = 7.8, 3.0, 1.3 Hz, Ar*H*), 7.94 – 7.85 (3H, m, Ar*H*), 7.71 (1H, dd, *J* = 3.0, 1.3 Hz, Ar*H*), 7.70 (1H, d, *J* = 1.3 Hz, Ar*H*), 7.54 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.22 (1H, ddd, *J* = 5.6, 4.9, 3.0 Hz, Ar*H*), 6.94 – 6.87 (2H, m, Ar*H*), 3.75 (3H, s, OCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.4 (Ar*C*OMe), 155.1 (Ar*C*N), 149.8 (Ar*C*HN), 143.0 (Ar*C*), 140.6 (Ar*C*), 137.0 (Ar*C*H), 132.9 (Ar*C*), 131.1 (Ar*C*H), 129.9 (2 × Ar*C*H), 129.7 (Ar*C*H), 127.5 (Ar*C*H), 125.6 (Ar*C*H), 123.0 (Ar*C*H), 120.6 (Ar*C*H), 114.6 (2 × Ar*C*H), 55.6 (O*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{18}H_{15}NO_3S$ $[M+Na]^+$: 348.0670, found 348.0672.

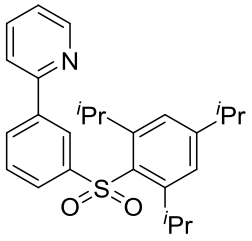
2-(3-(Mesitylsulfonyl)phenyl)pyridine (318i)



Following General Procedure I, 2-phenylpyrdine (140 µL, 1.0 mmol) and 2-mesitylenesulfonyl chloride (0.64 g, 2.9 mmol) in dry MeCN (3 mL) were reacted and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a yellow amorphous solid (16.4 mg, 5%); ν_{max} (neat) / cm^{-1}; 1602, 1586, 1564, 1459; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.69 (1H, d, *J* = 4.6 Hz, Ar*H*), 8.45 (1H, app t, *J* = 1.5 Hz, Ar*H*), 8.24 – 8.23 (1H, m, Ar*H*), 7.80 – 7.72 (3H, m, Ar*H*), 7.56 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.29 -7.26 (1H, m, Ar*H*), 6.95 (2H, s, Ar*H*), 2.63 (6H, s, 2 × ArCH_3), 2.29 (3H, s, ArCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.6 (Ar*C*N), 150.1 (Ar*C*HN), 144.2 (Ar*C*), 143.6 (Ar*C*), 140.5 (Ar*C*), 140.2 (2 × Ar*C*), 137.2 (Ar*C*H), 133.9 (Ar*C*), 132.4 (2 × Ar*C*H), 131.2 (Ar*C*H),

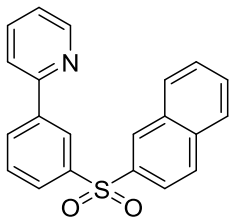
129.5 (Ar*C*H), 126.7 (Ar*C*H), 124.6 (Ar*C*H), 123.1 (Ar*C*H), 120.8 (Ar*C*H), 23.0 (2 × Ar*C*H_3), 21.1 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{20}H_{19}NO_2S$ $[M+Na]^+$: 360.1034; found: 360.1025.

2-(3-((2,4,6-Triisopropylphenyl)sulfonyl)phenyl)pyridine (318j)



Following General Procedure I, 2-phenylpyrdine (140 μL, 1.0 mmol) and 2,4,6-triisopropylbenzenesulfonyl chloride (0.89 g, 2.9 mmol) in dry MeCN (3 mL) were reacted and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a yellow solid (32 mg, 11%); mpt. 149 – 157 °C; ν_{max} (neat) / cm^{-1}; 3076, 2955, 2925, 2867, 1729, 1599, 1586, 1563, 1459, 1425, 1407; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.72 (1H, d, *J* = 4.4 Hz, Ar*H*), 8.46 (1H, app t, *J* = 1.7 Hz, Ar*H*), 8.28 (1H, d, *J* = 7.7, Ar*H*), 7.83 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.77 (1H, d, *J* = 7.7 Hz, Ar*H*), 7.74 – 7.70 (1H, m, Ar*H*), 7.59 (1H, t, *J* = 7.7 Hz, Ar*H*), 7.35 – 7.29 (1H, m, Ar*H*), 7.18 (2H, s, Ar*H*), 4.24 (2H, hept, *J* = 7.0 Hz, C*H*Me_2), 2.91 (1H, hept, *J* = 7.0 Hz, C*H*Me_2), 1.28 (6H, d, *J* = 7.0 Hz, 2 × CHCH_3), 1.18 (12H, d, *J* = 7.0 Hz, 4 × CHCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 154.1 (Ar*C*N), 151.6 (2 × Ar*C* & Ar*C*HN), 151.0 (2 × Ar*C*), 146.0 (Ar*C*), 132.3 (Ar*C*), 131.0 (Ar*C*H), 129.7 (Ar*C*H), 126.4 (Ar*C*H), 124.3 (2 × Ar*C*H), 124.0 (2 × Ar*C*H), 123.3 (Ar*C*H), 121.0 (Ar*C*H), 29.8 (Ar*C*HMe_2), 29.7 (2 × Ar*C*HMe_2), 24.8 (4 × *C*H_3), 23.7 (2 × *C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{26}H_{31}NO_2S$ $[M+H]^+$: 422.2154, found: 422.2159.

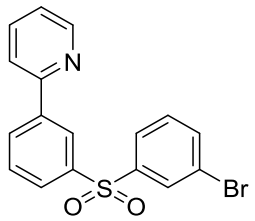
2-(3-(Naphthalen-2-ylsulfonyl)phenyl)pyridine (318k)



Following General Procedure I, 2-phenylpyrdine (140 μL, 1.0 mmol) and 1-naphthalenesulfonyl chloride (0.64 g, 2.8 mmol) in dry MeCN were reacted and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a white solid (214 mg,

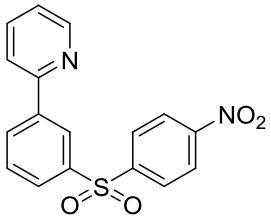
63%); mpt. 120 – 124 °C; ν_{max} (neat) / cm^{-1}; 3069, 1586, 1561, 1460; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.68 – 8.61 (3H, m, Ar*H*), 8.17 (1H, d, *J* = 7.8 Hz, Ar*H*), 8.03 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.91 – 7.84 (3H, m, Ar*H*), 7.77 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.69 (1H, s, Ar*H*), 7.68 (1H, d, *J* = 1.0 Hz, Ar*H*), 7.58 – 7.48 (3H, m, Ar*H*), 7.22 – 7.17 (1H, m, Ar*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 154.9 (Ar*C*N), 149.7 (Ar*C*HN), 142.2 (Ar*C*), 140.6 (Ar*C*), 138.2 (Ar*C*), 137.0 (Ar*C*H), 134.9 (Ar*C*), 132.1 (Ar*C*), 131.4 (Ar*C*H), 129.8 (Ar*C*H), 129.7 (Ar*C*H), 129.3 (Ar*C*H), 129.1 (Ar*C*H), 129.1 (Ar*C*H), 127.9 (Ar*C*H), 127.8 (Ar*C*H), 127.6 (Ar*C*H), 125.9 (Ar*C*H), 123.0 (Ar*C*H), 122.6 (Ar*C*H), 120.6 (Ar*C*H); HRMS (ESI μTOF) m/z calcd for $C_{21}H_{15}NO_2S$ $[M+H]^+$: 346.0902, found 346.0900.

2-(3-((3-Bromophenyl)sulfonyl)phenyl)pyridine (318l)



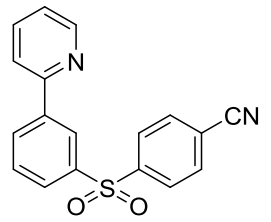
Following General Procedure I, 2-phenylpyrdine (140 μL, 1.0 mmol) and 3-bromobenzenesulfonyl chloride (0.74 g, 2.9 mmol) in dry MeCN (3 mL) were reacted and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a brown oil (115 mg, 31%); ν_{max} (neat) / cm^{-1}; 3105, 3052, 2926, 1606, 1587, 1532, 1460, 1434, 1411; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.69 (1H, app d, *J* = 3.9 Hz, Ar*H*), 8.57 (1H, s, Ar*H*), 8.24 (1H, d, *J* = 7.7 Hz, Ar*H*), 8.11 (1H, app d, *J* = 1.5 Hz, Ar*H*), 8.00 – 7.85 (2H, m, Ar*H*), 7.83 – 7.70 (2H, m, Ar*H*), 7.70 – 7.57 (2H, m, Ar*H*), 7.36 (1H, t, *J* = 7.9 Hz, Ar*H*), 7.32 – 7.24 (1H, m, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.0 (Ar*C*N), 150.0 (Ar*C*HN), 143.5 (Ar*C*), 141.5 (Ar*C*), 141.0 (Ar*C*), 137.2 (Ar*C*H), 136.4 (Ar*C*H), 132.0 (Ar*C*H), 131.0 (Ar*C*H), 130.5 (Ar*C*H), 130.0 (Ar*C*H), 128.1 (Ar*C*H), 126.4 (Ar*C*H), 126.2 (Ar*C*H), 123.3 (Ar*C*Br), 123.2 (Ar*C*H), 120.8 (Ar*C*H); HRMS (ESI μTOF) m/z calcd for $C_{17}H_{12}{}^{79}BrNO_2S$ $[M+Na]^+$: 395.9670, found: 395.9680.

2-(3-((4-Nitrophenyl)sulfonyl)phenyl)pyridine (318m)



Following General Procedure I, 2-phenylpyridine (140 µL, 1.0 mmol) and 4-nitrobenzenesulfonyl chloride (0.66 g, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by flash column chromatography eluting with (EtOAc/Et_2O/hexane) (1.5/0.5/8) to give the desired product as an orange solid (31 mg, 9%); mpt. 158 – 160 °C; ν_{max} (neat) / cm^{-1}; 3106, 3052, 1607, 1588, 1532, 1461, 1434, 1411; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.72 (1H, s, Ar*H*), 8.61 (1H, s, Ar*H*), 8.35 (1H, s, Ar*H*), 8.33 (1H, d, s, Ar*H*), 8.27 (1H, d, *J* = 7.9 Hz, Ar*H*), 8.19 (1H, s, Ar*H*), 8.17 (1H, s, Ar*H*), 8.00 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.82 (1H, td, *J* = 7.8, 1.4 Hz, Ar*H*), 7.77 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.66 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.33 (1H, dd, *J* = 7.8, 1.4 Hz, Ar*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 154.8 (Ar*C*N), 150.5 (Ar*C*NO_2), 150.0 (Ar*C*S), 147.4 (Ar*C*HN), 141.1 (Ar*C*S), 140.9 (Ar*C*H), 137.5 (Ar*C*), 132.5 (Ar*C*H), 130.3 (Ar*C*H), 129.2 (2 × Ar*C*H), 128.4 (Ar*C*H), 126.6 (Ar*C*H), 124.7 (2 × Ar*C*H), 123.5 (Ar*C*H), 120.9 (Ar*C*H); HRMS (ESI µTOF) m/z calcd for $C_{17}H_{12}N_2O_4S$ $[M+H]^+$: 341.0596, found: 341.0574.

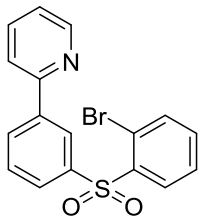
4-((3-(Pyridin-2-yl)phenyl)sulfonyl)benzonitrile (318n)



Follwoing General Procedure I, 2-phenylpyrdine (140 µL, 1.0 mmol) and 4-cyanobenzenednesulfonyl chloride (0.59 g, 2.9 mmol) in dry MeCN (3 mL) were reacted and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a beige amorphous solid (14 mg, 4%); ν_{max} (neat) / cm^{-1}; 3091, 2926, 2856, 2234, 1725, 1587, 1533, 1460, 1434, 1410; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.71 (1H, ddd, *J* = 4.9, 1.1, 0.5 Hz, Ar*H*), 8.59 (1H, app t, *J* = 1.7 Hz, Ar*H*), 8.27 (1H, ddd, *J* = 7.7, 1.7, 1.1 Hz, Ar*H*), 8.12 – 8.08 (2H, m, Ar*H*), 7.98 (1H, ddd, *J* = 7.7, 1.7, 1.1 Hz, Ar*H*), 7.84 – 7.78 (3H, m, Ar*H*), 7.76 (1H, dt, *J* = 7.4, 0.5 Hz, Ar*H*), 7.65 (1H, t, *J* = 7.7 Hz, Ar*H*), 7.31 (1H, ddd, *J* = 7.4, 4.9, 1.1 Hz, Ar*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.0 (Ar*C*N), 150.2 (Ar*C*H), 145.9 (Ar*C*), 141.3 (Ar*C*), 140.9 (Ar*C*), 137.3 (Ar*C*H), 133.3 (2 × Ar*C*H), 132.4

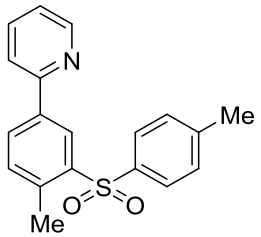
(Ar*C*H), 130.3 (Ar*C*H), 128.5 (2 × Ar*C*H), 128.3 (Ar*C*H), 126.5 (Ar*C*H), 123.4 (Ar*C*H), 120.8 (Ar*C*H), 117.3 (*C*N), 117.1 (Ar*C*CN); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{12}N_2O_2S$ $[M+Na]^+$: 321.0692, found: 321.0739.

2-(3-((2-Bromophenyl)sulfonyl)phenyl)pyridine (318o)



To a solution of $[RuCl_2(p\text{-cymene})]_2$ (7.8 mg, 0.1 mmol), K_2CO_3 (75 mg, 0.5 mmol), 2-phenylpyrdine (45 μL, 0.3 mmol) and 2-bromobenzenesulfonyl chloride (0.19 g, 0.8 mmol) in MeCN (1 mL) were reacted using general procedure I and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a white amorphous solid (16 mg, 18%); ν_{max} ($CDCl_3$) / cm^{-1}; 3065, 2953, 2924, 2854, 1721, 1587, 1574, 1565, 1460, 1446, 1432, 1410; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.70 (1H, app d, *J* = 4.8 Hz, Ar*H*), 8.56 (1H, app t, *J* = 1.7 Hz, Ar*H*), 8.45 (1H, dd, *J* = 7.9, 1.7 Hz, Ar*H*), 8.31 (1H, dt, *J* = 7.8, 1.2 Hz, ArH), 7.98 (1H, ddd, *J* = 7.9, 1.7, 1.0 Hz, Ar*H*), 7.85 – 7.73 (2H, m, Ar*H*), 7.67 – 7.60 (2H, m, Ar*H*), 7.56 (1H, td, *J* = 7.8, 1.2 Hz, Ar*H*), 7.43 (1H, td, *J* = 7.9, 1.7 Hz, Ar*H*), 7.30 (1H, ddd, *J* = 6.6, 4.8, 1.7 Hz, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.2 (Ar*C*N), 149.9 (Ar*C*H), 140.6 (Ar*C*), 140.2 (Ar*C*), 139.9 (Ar*C*), 137.4 (Ar*C*H), 135.8 (Ar*C*H), 134.8 (Ar*C*H), 132.0 (Ar*C*H), 131.7 (Ar*C*H), 129.5 (Ar*C*H), 129.1 (Ar*C*H), 128.1 (Ar*C*H), 127.1 (Ar*C*H), 123.2 (Ar*C*H), 121.3 (Ar*C*Br), 121.0 (Ar*C*H); HRMS (ESI μTOF) m/z calcd for $C_{17}H_{12}{}^{79}BrNO_2S$ $[M+H]^+$: 373.9850, found: 373.9879.

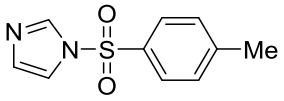
2-(4-Methyl-3-tosylphenyl)pyridine (324)



Following General Procedure I, 2-(*p*-tolyl)pyridine (170 μL, 1.0 mmol) and *p*-toluenesulfonyl chloride (0.57 g, 3.0 mmol) in dry MeCN (3 mL) were reacted and the product was purified by

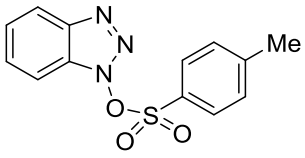
flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a pale yellow solid (132 mg, 41%); mpt. 138 – 142 °C; ν_{max} (neat) / cm^{-1}; 3081, 1596, 1520, 1490, 1478; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.82 (1H, d, *J* = 1.9 Hz, Ar*H*), 8.66 (1H, dt, *J* = 4.8 ,1.2 Hz, Ar*H*), 8.12 (1H, dd, *J* = 8.0, 1.9 Hz, Ar*H*), 7.79 – 7.72 (4H, m, Ar*H*), 7.28 (1H, d, *J* = 8.0 Hz, Ar*H*), 7.26 – 7.19 (3H, m, Ar*H*), 2.43 (3H, s, CH_3), 2.34 (3H, s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.3 (Ar*C*N), 149.8 (Ar*C*HN), 144.0 (Ar*C*S), 139.5 (Ar*C*), 138.3 (Ar*C*), 138.2 (Ar*C*), 137.9 (Ar*C*), 137.0 (Ar*C*H), 133.2 (Ar*C*H), 131.6 (Ar*C*H), 129.7 (2 × Ar*C*H), 127.7 (2 × Ar*C*H), 127.5 (Ar*C*H), 122.7 (Ar*C*H), 120.4 (Ar*C*H), 21.5 (Ar*C*H_3), 20.0 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{19}H_{17}NO_2S$ $[M+Na]^+$: 346.0878, found: 346.0887.

1-Tosyl-1*H*-imidazole (320)[2]



A solution of imidazole (1.38 g, 20.3 mmol) in dry dichloromethane (10 mL) was stirred at 0 °C for 1.5 h under N_2. In a separate flask, a solution of *p*-toluenesulfonyl chloride (recrsytallised) (1.74 g, 9.1 mmol) in dry dichloromethane (10 mL) was stirred at rt for 1.5 h under N_2. The *p*-toluenesulfonyl chloride solution was added dropwise slowly to the imidazole solution over 30 min at 0 °C, and then the reaction mixture was allowed to warm to rt and left to stir under N_2 for 17 h. The resulting reaction mixture was filtered through a pad of silica and washed with hexane (20 mL) followed by a mixture of EtOAc/hexane (1:1) (300 mL). The filtrate was concentrated *in vacuo* and the oil residue was dissolved in a minimum amount of EtOAc (1.5 mL) and precipitated out with hexane (70 mL) to give a white suspension. The white precipitate was filtered under vacuum and washed with hexane (125 mL) to afford the title product as a white fluffy solid (1.39 g, 68 %); mpt. 71 – 76 °C (lit.[2] 74.5 – 76 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.01 (1H, s, NC*H*N), 7.85 – 7.79 (2H, m, ArC*H*), 7.35 (2H, d, *J* = 8.1 Hz, ArC*H*), 7.29 (1H, t, *J* = 1.4 Hz, SO_2NC*H*), 7.08 (1H s, ArC*H*,), 2.44 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.5 (Ar*C*Me), 136.8 (Ar*C*HN), 135.1 (Ar*C*), 131.6 (Ar*C*HN), 130.6 (2 × Ar*C*H), 127.5 (2 × Ar*C*H), 117.6 (Ar*C*HN), 21.9 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{10}H_{10}N_2O_2S$ $[M+H]^+$: 223.0541, found: 223.0535.

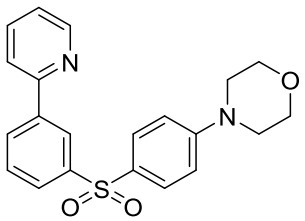
1*H*-Benzo[*d*][1,2,3]triazol-1-yl 4-methylbenzenesulfonate (321)[3]



To a solution of 1-hydroxybenzotriazole hydrate (0.99 g, 7.4 mmol) in dry dichloromethane (30 mL) was added imidazole (0.51 g, 7.6 mmol). The mixture was cooled to 0 °C under N_2 and added a solution of *p*-toluenesulfonyl chloride (recrystallised) (1.43 g, 7.5 mmol) in dichloromethane (4 mL) dropwise over a 10 min period. The reaction mixture was stirred and warmed to rt and stirred at rt for a further 3 h. Next, the reaction mixture was diluted with dichloromethane (30 mL) and filtered in a sintered funnel over anhydrous $MgSO_4$ under an atmosphere of N_2. The solvent was removed *in vacuo* and the resulting colourless residue was recrystallised from dry dichloromethane/ hexane. The product was filtered by gravity to afford the title compound as a white crystalline solid (1.46 g, 69 %); mpt. 80 – 85 °C (lit.[3] 80 – 81 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.02 – 7.99 (1H, m, Ar*H*), 7.81 – 7.75 (2H, m, Ar*H*), 7.65 (1H, dt, *J* = 8.3, 1.0 Hz, Ar*H*), 7.62 – 7.55 (1H, m, Ar*H*), 7.47 – 7.38 (3H, m, Ar*H*), 2.50 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.6 (Ar*C*SO_2), 139.8 (Ar*C*), 134.6 (Ar*C*), 131.2 (Ar*C*H), 129.8 (Ar*C*H), 129.2 (2 × Ar*C*H), 128.9 (Ar*C*), 125.9 (2 × Ar*C*H), 114.6 (Ar*C*H), 112.5 (Ar*C*H), 21.4 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{13}H_{11}N_3O_3S$ $[M+Na]^+$: 312.0419, found: 312.0399.

Sequential synthesis of sulfonated products

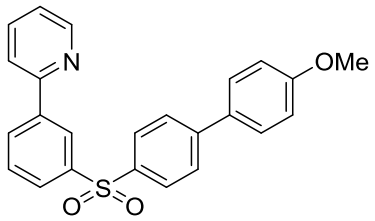
4-(4-((3-(Pyridin-2-yl)phenyl)sulfonyl)phenyl)morpholine (327)[4]



To a nitrogen-purged carousel tube was added $Pd(dba)_2$ (12 mg, 0.02 mmol), ^{t}BuONa (65 mg, 0.7 mmol), 1,1-biphenyl-2-yldi-tert-butylphosphine (7.3 mg, 0.02 mmol), 2-(3-((4-bromophenyl)sulfonyl)phenyl)pyridine **318b** (93 mg, 0.3 mmol), morpholine (17.5 μL, 0.2 mmol) in dry toluene (3 mL). The reaction mixture was heated at 80 °C with stirring for 20 h, afterwards the reaction mixture was cooled down to rt and then the solvent was removed under reduced pressure. The product was purified by flash column chromatography eluting with (EtOAc/petrol)

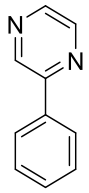
(3/7) to give the desired product as a yellow solid (66 mg, 70%); mpt. 100 – 105 °C; ν_{max} (neat) / cm^{-1}; 3060, 2964, 2877, 2836, 1587, 1561, 1506, 1468, 1446, 1433; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.68 (1H, d, *J* = 4.4 Hz, Ar*H*), 8.51 (1H, t, *J* = 1.5 Hz, Ar*H*), 8.17 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.92 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.86 – 7.78 (2H, m, Ar*H*), 7.77 – 7.72 (2H, m, Ar*H*), 7.56 (1H, t, *J* = 7.8 Hz, Ar*H*), 7.26 (1H, td, *J* = 5.3, 2.0 Hz, Ar*H*), 6.89 – 6.82 (2H, m, Ar*H*), 3.79 (4H, t, *J* = 5.0 Hz, 2 × CH_2), 3.23 (4H, t, *J* = 5.0 Hz, 2 × CH_2); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.5 (Ar*C*N), 154.2 (Ar*C*HN), 149.9 (Ar*C*), 143.5 (Ar*C*H), 140.6 (Ar*C*), 137.1 (Ar*C*H), 131.1 (Ar*C*H), 129.9 (Ar*C*H), 129.7 (Ar*C*H), 129.6 (2 × Ar*C*H), 127.5 (Ar*C*H), 125.5 (Ar*C*H), 123.1 (Ar*C*), 120.8 (Ar*C*), 113.9 (2 × Ar*C*H), 66.5 (2 × *C*H_2), 47.4 (2 × *C*H_2); HRMS (ESI μTOF) m/z calcd for $C_{21}H_{20}N_2O_3S$ $[M+H]^+$: 381.1273; found: 381.1271.

2-(3-((4'-Methoxy-[1,1'-biphenyl]-4-yl)sulfonyl)phenyl)pyridine (328)[5]



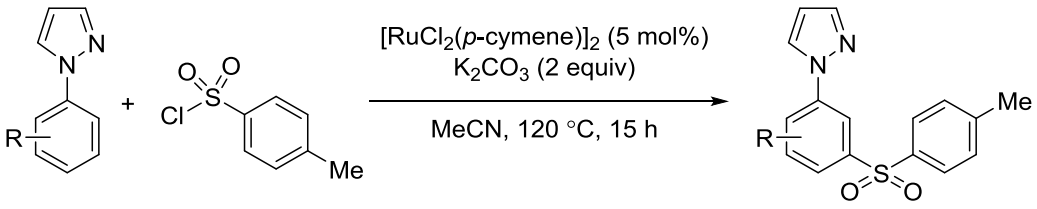
To a nitrogen-purged carousel tube was added $Pd(PPh_3)_4$ (7 mg, 0.006 mmol) 2-(3-((4-bromophenyl)sulfonyl)phenyl)pyridine **318b** (90 mg, 0.2 mmol), 4-methoxyphenylboronic acid (79 mg, 0.5 mmol) in dry toluene (3 mL), absolute ethanol (1 mL) and 2 M Na_2CO_3 (0.43 mL). The reaction mixture was heated at 80 °C with stirring for 18 h, after this time the reaction mixture was cooled to rt and the solvent was removed under reduced pressure. The crude mixture was washed with water (10 mL) then extracted with EtOAc (6 × 10 mL), the organics were dried over $MgSO_4$, filtered and evaporated under reduced pressure. The product was purified by flash column chromatography eluting with (EtOAc/ petrol) (3/7) to give the desired product as a white solid (87 mg, 90%); mpt. 128 – 130 °C; ν_{max} (neat) / cm^{-1}; 3061, 2971, 2941, 2843, 1607, 1590, 1520, 1485, 1471, 1437; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.70 (1H, dt, *J* = 4.8, 1.4 Hz, Ar*H*), 8.60 (1H, t, *J* = 1.7 Hz, Ar*H*), 8.26 – 8.21 (1H, m, Ar*H*), 8.03 – 7.98 (3H, m, Ar*H*), 7.78 (1H, dd, *J* = 3.3, 1.4 Hz, Ar*H*), 7.77 (1H, d, *J* = 1.4 Hz, Ar*H*), 7.67 – 7.58 (3H, m, Ar*H*), 7.52 – 7.47 (2H, m, Ar*H*), 7.31 – 7.26 (1H, m, Ar*H*), 7.00 – 6.94 (2H, m, Ar*H*), 3.83 (3H, s, OCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 160.3 (Ar*C*OMe), 155.4 (Ar*C*N), 150.1 (Ar*C*HN), 145.9 (Ar*C*), 142.6 (Ar*C*), 140.9 (Ar*C*), 139.4 (Ar*C*), 137.2 (Ar*C*H), 131.6 (Ar*C* & Ar*C*H), 129.9 (Ar*C*H), 128.6 (2 × Ar*C*H), 128.4 (2 × Ar*C*H), 128.0 (Ar*C*H), 127.5 (2 × Ar*C*H), 126.0 (Ar*C*H), 123.2 (Ar*C*H), 120.8 (Ar*C*H), 114.6 (2 × Ar*C*H), 55.5 (O*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{24}H_{19}NO_3S$ $[M+H]^+$: 402.1164, found: 402.1161.

2-Phenylpyrazine (330)[6]



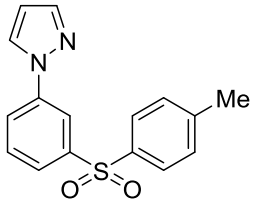
$PdCl_2$ (1.6 mg, 0.009 mmol), K_3PO_4 (0.22 g, 1.0 mmol) and benzeneboronic acid (0.22 g, 0.7 mmol) in DMF (2 mL) and distilled water (2 mL) with 2-chloropyrazine (45 µL, 0.5 mmol) was stirred at rt for 41 h in air. Then the reaction mixture was quenched with brine (sat.) (15 mL) and the resulting solution was diluted with Et_2O (15 mL) and the organic material was washed with water (3 × 50 mL). The organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The product was purified by flash column chromatography eluting with (EtOAc/ petrol) (5/95) to afford a white solid (51 mg, 70%); mpt. 74 – 79 °C (lit.[7] 72 – 73 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.03 (1H, s, Ar*H*), 8.63 (1H, s, Ar*H*), 8.50 (1H, s, Ar*H*), 8.03 – 7.99 (2H, m, Ar*H*), 7.55 – 7.45 (3H, m, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 153.0 (Ar*C*N), 144.3 (Ar*C*H), 143.0 (Ar*C*H), 142.3 (Ar*C*H), 136.5 (Ar*C*), 130.0 (Ar*C*H), 129.2 (2 × Ar*C*H), 127.1 (2 × Ar*C*H).; HRMS (ESI µTOF) m/z calcd for $C_{10}H_8N_2$, $[M+H]^+$: 157.0766, found: 157.0763.

5.2.2. General procedure II



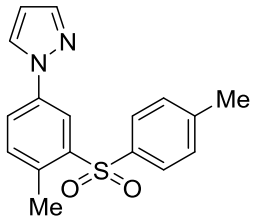
To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (30 mg, 0.05 mmol) and dry acetonitrile (3 mL) and the solution was stirred under N_2. To this was added 1-phenylpyrazole derivatives (1.0 mmol), K_2CO_3 (0.27 g, 2.0 mmol) and the *p*-toluenesulfonyl chloride (3.0 mmol) and the reaction mixture was purged under N_2 then heated at 120 °C with stirring. After 15 h, the reaction mixture was cooled to rt and the crude mixture was quenched with water (1 mL) and the organic material was extracted with dichloromethane (6 × 20 mL). The organics were dried over $MgSO_4$, filtered and the solvent was removed *in vacuo*. The product is then purified by silica flash column chromatography with the appropriate eluent.

1-(3-Tosylphenyl)-1*H*-pyrazole (332a)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and *p*-toluenesulfonyl chloride (0.57 g, 3.0 mmol) in dry MeCN (3 mL) were reacted under the general procedure II and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a yellow solid (41 mg, 14%); mpt. 140 – 142 °C; ν_{max} (neat) / cm^{-1}; 1644, 1585, 1446; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.23 (1H, t, *J* = 1.8 Hz, Ar*H*), 7.99 – 7.97 (1H, m, Ar*H*), 7.92 (1H, ddd, *J* = 8.0, 1.9, 1.0 Hz, Ar*H*), 7.88 – 7.83 (2H, m, Ar*H*), 7.81 (1H, ddd, *J* = 8.0, 1.9, 1.0 Hz, Ar*H*), 7.73 (1H, d, *J* = 1.8 Hz, Ar*H*), 7.57 (1H, t, *J* = 8.0 Hz, Ar*H*), 7.30 (2H, d, *J* = 8.0 Hz, Ar*H*), 6.50 (1H, dd, *J* = 2.5, 1.8 Hz, Ar*H*), 2.39 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.7 (Ar*C*S), 143.6 (Ar*C*N), 142.0 (Ar*C*HN), 140.9 (Ar*C*), 138.2 (Ar*C*), 130.7 (Ar*C*H), 130.2 (2 × Ar*C*H), 127.9 (2 × Ar*C*H), 127.0 (Ar*C*H), 125.1 (Ar*C*H), 123.4 (Ar*C*H), 117.7 (Ar*C*H), 108.7 (Ar*C*H), 21.7 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{16}H_{14}N_2O_2S$ $[M+H]^+$: 373.9848, found: 373.9845

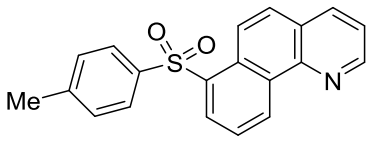
1-(4-Methyl-3-tosylphenyl)-1*H*-pyrazole (332b)



To a solution of 1-(*p*-tolyl)-1*H*-pyrazole **334a** (0.15 g, 1.0 mmol) and *p*-toluenesulfonyl chloride (0.57 g, 3.0 mmol) in dry MeCN (3 mL) were reacted under the general procedure II and the product was purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a yellow solid (31 mg, 10%); mpt. 140 – 149 °C; ν_{max} (neat) / cm^{-1}; 3138, 3994, 1609, 1597, 1520, 1494; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.49 (1H, d, *J* = 2.3 Hz, Ar*H*), 8.02 (1H, d, *J* = 2.4 Hz, Ar*H*), 7.89 (1H, dd, *J* = 8.4, 2.4 Hz, Ar*H*), 7.81 – 7.75 (2H, m, Ar*H*), 7.75 (1H, d, *J* = 1.7 Hz, Ar*H*), 7.30 (3H, d, *J* = 8.4 Hz, Ar*H*), 6.52 (1H, t, *J* = 1.7 Hz, Ar*H*), 2.44 (3H, s, ArCH_3), 2.41 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.5 (Ar*C*S), 141.8 (Ar*C*N), 140.3 (Ar*C*), 138.8 (Ar*C*), 137.9 (Ar*C*), 135.7 (Ar*C*H), 134.0 (Ar*C*H), 129.9 (2 × Ar*C*H), 128.0 (2 × Ar*C*H), 127.1 (Ar*C*H), 124.0 (Ar*C*H),

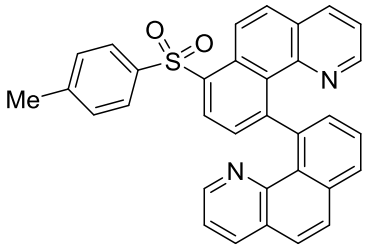
119.5 (Ar*C*H), 108.4 (Ar*C*H), 21.7 (Ar*C*H_3), 19.8 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{17}H_{16}N_2O_2S$ $[M+H]^+$: 313.1011, found: 313.0993.

7-Tosylbenzo[*h*]quinoline (337a)



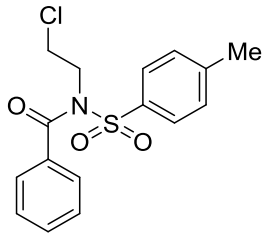
To a N_2 purged oven-dried flask was added $[RuCl_2(p\text{-cymene})]_2$ (90 mg, 0.2 mmol), K_2CO_3 (0.84 g, 6.1 mmol), *p*-toluenesulfonyl chloride (1.75 g, 9.2 mmol) and benzo[*h*]quinoline (0.54 g, 3.0 mmol) in dry MeCN (9 mL) and heated the reaction mixture up to 120 °C for 48 h under an atmosphere of N_2. The reaction mixture kept drying out therefore additional MeCN (40 mL) was added. Then the reaction mixture was cooled to rt and quenched with water (3 mL) and diluted with dichloromethane (50 mL) and washed with water (50 mL). The organic material was extracted with dichloromethane (3 × 50 mL). The combined organic extracts were dried over $MgSO_4$ and filtered, then concentrated *in vacuo*. The deep brown residue was purified by flash column chromatography twice; column 1, eluent: (EtOAc/ hexane) (2/8); column 2, eluent: (IPA/dichloromethane) (0.5/99.5), and afforded the title compound as a beige powder (68 mg, 7%); mpt. 130 – 141 °C; ν_{max} (neat) / cm^{-1}; 3040, 1723, 1619, 1598, 1560, 1494, 1409; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.67 (1H, d, *J* = 8.2 Hz, Ar*H*), 9.00 (1H, dd, *J* = 4.4, 1.4 Hz, Ar*H*), 8.68 (1H, d, *J* = 9.3 Hz, Ar*H*), 8.67 (1H, dd, *J* = 7.8, 1.4 Hz, Ar*H*), 8.17 (1H, dd, *J* = 7.8, 1.4 Hz, Ar*H*), 7.90 – 7.83 (3H, m, Ar*H*), 7.79 (1H, d, *J* = 9.3 Hz, Ar*H*), 7.56 (1H, dd, *J* = 8.0, 4.4 Hz, Ar*H*), 7.26 (2H, d, *J* = 8.2 Hz, Ar*H*), 2.34 (3H, s, Ar*C*H_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.6 (Ar*C*HN), 145.8 (Ar*C*N), 144.2 (Ar*C*), 139.0 (Ar*C*), 136.5 (Ar*C*), 136.1 (Ar*C*), 132.9 (Ar*C*), 131.1 (Ar*C*H), 131.0 (Ar*C*H), 129.9 (2 × Ar*C*H), 129.6 (Ar*C*), 128.1 (Ar*C*H), 127.6 (2 × Ar*C*H), 126.0 (Ar*C*H), 125.9 (Ar*C*H), 123.1 (Ar*C*H), 122.9 (Ar*C*H), 21.7 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{20}H_{15}NO_2S$ $[M+Na]^+$: 356.0721, found: 356.0734.

7-Tosyl-10,10'-bibenzo[*h*]quinoline (337b)



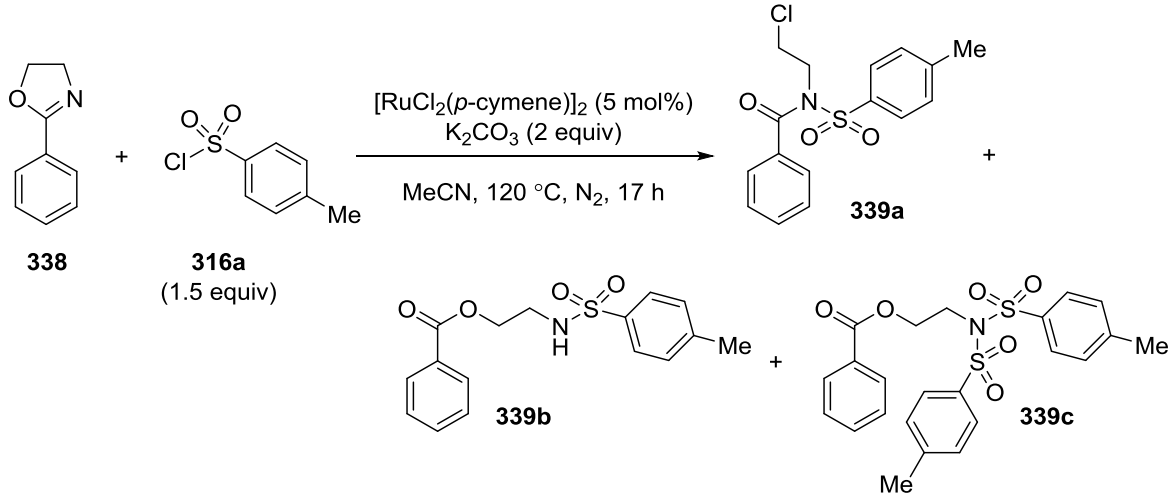
To a N_2 purged oven-dried flask was added $[RuCl_2(p\text{-cymene})]_2$ (0.09 g, 0.2 mmol), K_2CO_3 (0.84 g, 6.1 mmol), *p*-toluenesulfonyl chloride (1.75 g, 9.2 mmol) and benzo[*h*]quinoline (0.54 g, 3.0 mmol) in dry MeCN (9 mL) and heated the reaction mixture up to 120 °C for 48 h under an atmosphere of N_2. The reaction mixture kept drying so additional MeCN (40 mL) was addd to the reaction. Then the reaction mixture was cooled to rt and quenched with water (3 mL) and diluted with dichloromethane (50 mL) and washed with water (50 mL). The organic material was extracted with dichloromethane (3 × 50 mL). The combined organic extracts were dried over $MgSO_4$ and filtered, then concentrated *in vacuo*. The deep brown residue was purified by column chromatography twice; column 1, eluent: (EtOAc/ hexane) (2/8); column 2, eluent: (IPA/dichloromethane) (0.5/99.5), and afforded the titled compound as a beige fluffy powder (103 mg, 7%); mpt. 221 – 226 °C; ν_{max} (neat) / cm^{-1}; 3042, 2256, 2164, 2032, 1724, 1619, 1598, 1560, 1494, 1409; ^1H NMR (500 MHz, $CDCl_3$) δ 8.82 (1H, d, *J* = 9.3 Hz, Ar*H*), 8.69 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.98 (1H, dd, *J* = 8.0, 1.2 Hz, Ar*H*), 7.97 – 7.94 (2H, m, Ar*H*), 7.94 – 7.92 (2H, m, Ar*H*), 7.81 (1H, dd, *J* = 4.2, 1.8 Hz, Ar*H*), 7.73 – 7.69 (3H, m, Ar*H*), 7.65 (1H, d, *J* = 8.8 Hz, Ar*H*), 7.59 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.37 (1H, dd, *J* = 7.2, 1.2 Hz, Ar*H*), 7.33 (2H, d, *J* = 8.0 Hz, Ar*H*), 7.02 (2H, ddd, *J* = 7.9, 4.3, 1.8 Hz, Ar*H*), 2.41 (3H, s, ArCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 153.0 (Ar*C*N), 147.2 (Ar*C*HN), 146.8 (Ar*C*), 146.7 (Ar*C*), 146.5 (Ar*C*H), 144.0 (Ar*C*), 143.9 (Ar*C*), 139.9 (Ar*C*), 134.9 (Ar*C*H), 134.9 (Ar*C*H), 134.3 (Ar*C*), 133.8 (Ar*C*), 131.7 (Ar*C*), 130.5 (Ar*C*), 130.2 (Ar*C*H), 129.9 (2 × Ar*C*H), 129.7 (Ar*C*), 128.6 (Ar*C*H), 127.8 (Ar*C*H), 127.5 (Ar*C*H), 127.5 (3 × Ar*C*H), 127.3 (Ar*C*H), 126.9 (Ar*C*H), 126.8 (Ar*C*), 126.2 (Ar*C*), 125.4 (Ar*C*H), 123.4 (Ar*C*H), 121.2 (Ar*C*H), 120.5 (Ar*C*H), 21.7 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{33}H_{22}N_2O_2S$ $[M+H]^+$: 511.1480; found: 511.1490.

***N*-(2-Chloroethyl)-*N*-tosylbenzamide (339a)**



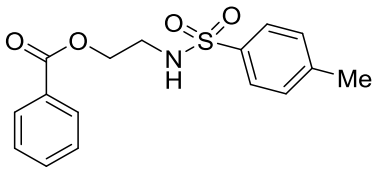
To a nitrogen-purged carousel tube was added 2-phenyl-2-oxazoline (200 µL, 1.5 mmol) and *p*-toluenesulfonyl chlroide (0.43 g, 2.3 mmol) and dry MeCN (3 mL). The reaction mixture was sealed under an atmosphere of nitrogen and was heated at 80 °C with stirring for 19 h, then the reaction mixture was cooled down to rt. The crude mixture was quenched with water (1 mL) and the organic material was extracted with dichloromethane (5 × 25 mL). The organic material was dried over $MgSO_4$, filtered and the solvent was removed *in vacuo*. The product was purified by flash column chromatography eluting with (EtOAc/petrol) (1/9) and the title compound was obtained as a white solid (441 mg, 87%); mpt. 77 – 84 °C; ν_{max} (neat) / cm^{-1}; 3096, 2160, 2007, 1670, 1596, 1493, 1449; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.62 – 7.57 (2H, m, Ar*H*), 7.41 – 7.36 (3H, m, Ar*H*), 7.29 – 7.22 (2H, m, Ar*H*), 7.17 (2H, d, *J* = 8.0 Hz, Ar*H*), 4.03 (2H, t, *J* = 6.5 Hz, CH_2Cl), 3.64 (2H, t, *J* = 6.5 Hz, CH_2N), 2.30 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.5 (Ar*C*=O), 145.2 (Ar*C*S), 135.5 (Ar*C*), 134.8 (Ar*C*), 131.8 (Ar*C*H), 129.7 (2 × Ar*C*H), 128.3 (2 × Ar*C*H), 128.3 (2 × Ar*C*H), 128.2 (2 × Ar*C*H), 48.4 (*C*H_2N), 42.0 (*C*H_2Cl), 21.6 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{16}H_{16}NO_3SCl$; $[M+Na]^+$: 360.0437, found: 360.0428.

5.2.3. General procedure III for the ruthenium catalysed ring-opening reaction



To a nitrogen-purged carousel tube was added [Ru(*p*-cymene)Cl_2]$_2$ (0.046 g, 0.08 mmol), 2-phenyl 2-oxazoline (200 µL, 1.5 mmol), *p*-toluenesulfonyl chlroide (0.85 g, 4.4 mmol), potassium carbonate (0.41 g, 3.0 mmol) and dry MeCN (3 mL). The reaction mixture was sealed under an atmosphere of nitrogen and was heated at 120 °C with stirring for 15 h, then the reaction mixture was cooled down to rt. The crude mixture was quenched with water (1 mL) and the organic material was extracted with dichloromethane (5 × 25 mL). The organic material was dried over $MgSO_4$, filtered and the solvent was removed *in vacuo*. The product was purified by flash column chromatography eluting with (EtOAc/petrol) (1/9).

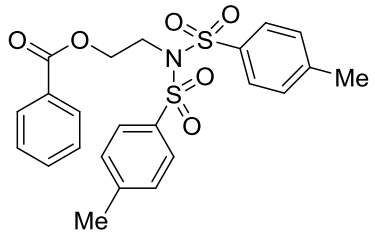
2-(4-Methyl-*N*-tosylphenylsulfonamido)ethyl benzoate (339b)



To a solution of 2-phenyl-2-oxazoline (200 µL, 1.5 mmol) and *p*-toluenesulfonyl chlroide (0.85 g, 4.4 mmol) in dry MeCN (3 mL) were reacted using general procedure III, the product was purified by flash column chromatography eluting with (EtOAc/ petrol) (1/9) to give the title compound as a white solid (260 mg, 54%); mpt. 90 – 114 °C; ν_{max} (neat) / cm^{-1}; 3265, 2907, 2856, 1699, 1636, 1597, 1582, 1542, 1493, 1453, 1425; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.93 – 7.90 (2H, m, Ar*H*), 7.73 (2H, d, *J* = 8.2 Hz, Ar*H*), 7.53 – 7.46 (1H, m, Ar*H*), 7.36 – 7.31 (2H, m, Ar*H*), 7.18 (2H, d, *J* = 8.2 Hz, Ar*H*), 5.80 (1H, t, *J* = 5.7 Hz, N*H*), 4.29 (2H, t, *J* = 5.7 Hz, C(O)OCH_2), 3.32 (2H, dd, *J* = 8.4, 5.7 Hz,

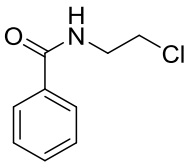
C*H*$_2$NH), 2.32 (3H, s, C*H*$_3$);. ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.3 (Ar*C*=O), 143.5 (Ar*C*), 136.8 (Ar*C*), 133.2 (Ar*C*H), 129.7 (2 × Ar*C*H), 129.7 (2 × Ar*C*H), 129.4 (Ar*C*), 128.3 (2 × Ar*C*H), 126.9 (2 × Ar*C*H), 63.4 (C(O)O*C*H$_2$), 42.2 (*C*H$_2$NH), 21.5 (Ar*C*H$_3$); HRMS (ESI μTOF) m/z calcd for $C_{16}H_{17}NO_4S$; $[M+Na]^+$: 342.0776, found: 342.0763.

2-(4-Methylphenylsufonamido)ethyl benzoate (339c)



To a solution of 2-phenyl-2-oxazoline (200 μL, 1.5 mmol) and *p*-toluenesulfonyl chlroide (0.85 g, 4.4 mmol) in dry MeCN (3 mL) were reacted using general procedure III, the product was purified by flash column chromatography eluting with (EtOAc/ petrol) (1/9) to give the title compound as a white solid (114 mg, 16%); mpt. 120 – 129 °C; ν_{max} (neat) / cm^{-1}; 2957, 2163, 1721, 1598, 1492, 1448; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.02 – 7.98 (2H, m, Ar*H*), 7.95 – 7.90 (4H, m, Ar*H*), 7.59 – 7.52 (1H, m, Ar*H*), 7.46 – 7.39 (2H, m, Ar*H*), 7.29 (4H, d, *J* = 8.1 Hz, Ar*H*), 4.50 (2H, t, *J* = 5.9 Hz, C(O)OC*H*$_2$), 4.09 (2H, t, *J* = 5.9 Hz, C*H*$_2$N), 2.41 (6H, s, 2 × C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.3 (Ar*C*=O), 145.2 (2 × Ar*C*), 136.8 (2 × Ar*C)*, 133.2 (Ar*C*H), 129.9 (2 × Ar*C*H), 129.9 (4 × Ar*C*H), 129.8 (Ar*C*), 128.5 (2 × Ar*C*H), 128.4 (4 × Ar*C*H), 62.6 (C(O)O*C*H$_2$), 47.0 (*C*H$_2$N), 21.8 (2 × Ar*C*H$_3$); HRMS (ESI μTOF) m/z calcd for $C_{23}H_{23}NO_6S_2$; $[M+Na]^+$: 496.0864, found: 496.0902.

***N*-(2-Chloroethyl)benzamide (339d)[8]**

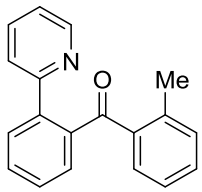


To a N_2 purged carousel tube was addded 2-phenyl 2-oxazoline (200 μL, 1.52 mmol) and *p*-toluenesulfonyl chloride (0.43 g, 2.3 mmol) in anhydrous DMF (3 mL) was heated at 60 °C for 15 h, then the reaction mixture was cooled down to rt. The crude mixture was diluted with EtOAc (25 mL) and washed with water (3 × 30 mL). The organic material was dried over $MgSO_4$, filtered and the solvent was removed *in vacuo*. The product was purified by flash column chromatography

eluting with (EtOAc/petrol) (1/9) and afforded the title compound as a white solid (41 mg, 15%); mpt. 96 – 104 °C (lit.[9] 86 – 87 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.80 (1H, s, Ar*H*), 7.78 (1H, d, *J* = 1.5 Hz, Ar*H*), 7.53 – 7.39 (3H, m, Ar*H*), 6.71 (1H, br s, N*H*), 3.84 – 3.76 (2H, m, 2 × C*H*), 3.75 – 3.71 (2H, m, 2 × C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.8 (Ar*C*=O), 134.2 (Ar*C*), 131.9 (Ar*C*H), 128.8 (2 × Ar*C*H), 127.1 (2 × Ar*C*H), 44.2 (NH*C*H_2), 41.8 (*C*H_2Cl); HRMS (ESI μTOF) m/z calcd for $C_9H_{10}NOCl$ $[M+Na]^+$: 206.0349, found: 206.0350.

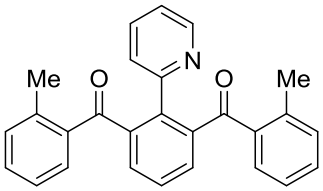
5.3. Chapter 3 Experimental Procedures

(2-(Pyridin-2-yl)phenyl)(*o*-tolyl)methanone (355a)[10]



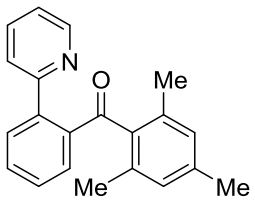
To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (0.031 g, 0.05 mmol) and dry toluene (3 mL) and the solution was stirred under N_2. To this was added 2-phenylpyridine (140 μL, 1.0 mmol), tricyclohexylphosphine (0.030 g, 0.1 mmol), K_2CO_3 (0.68 g, 4.9 mmol) and *o*-toluoyl chloride (320 μL, 2.5 mmol) and the reaction mixture was purged with N_2 and then heated at 120 °C with stirring. After 15 h the reaction mixture was allowed to cool to rt and the mixture was diluted with EtOAc (25 mL) and filtered through a pad of Celite®. The filtrate was washed with 1M NaOH (aq.) (50 mL) then washed with H_2O (2 × 50 mL). The organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The product was then purified by silica flash column chromatography eluting with (EtOAc/hexane) (2/8) to afford the title compound as a brown oil (163 mg, 61 %); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.42 (1H, d, *J* = 4.5 Hz, Ar*H*), 7.67 – 7.46 (5H, m, Ar*H*), 7.40 (1H, d, *J* = 7.6 Hz, Ar*H*), 7.19 – 7.11 (2H, m, Ar*H*), 7.07 (1H, d, *J* = 7.7 Hz, Ar*H*), 6.98 (1H, ddd, *J* = 7.6, 5.1, 0.9 Hz, Ar*H*), 6.92 (1H, t, *J* = 7.7 Hz, Ar*H*), 2.58 (3H, s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.8 (Ar*C*=O), 157.4 (Ar*C*H), 148.7 (Ar*C*), 140.7 (Ar*C*), 140.2 (Ar*C*), 139.1 (Ar*C*), 138.1 (Ar*C*H), 136.3 (Ar*C*H), 131.2 (Ar*C*H), 131.0 (Ar*C*H), 130.6 (Ar*C*H), 130.4 (Ar*C*H), 129.8 (Ar*C*H), 129.1 (Ar*C*H), 128.5 (Ar*C*H), 124.8 (Ar*C*H), 122.6 (Ar*C*H), 121.9 (Ar*C*H), 21.0 (Ar*C*H_3); HRMS (ESI μTOF) m/z calculated for $C_{19}H_{15}NO$ $[M+Na]^+$:274.1232, found: 274.1224.

(2-(Pyridin-2-yl)-1,3-phenylene)bis(*o*-tolylmethanone) (355b)[10]



To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (0.031 g, 0.05 mmol.) and dry toluene (3 mL) and the solution was stirred under N_2. To this was added 2-phenylpyridine (140 µL, 1.0 mmol), tricyclohexylphosphine (0.028 g, 0.1 mmol), $CuCl_2$ (0.017 g, 0.1 mmol), K_2CO_3 (0.69 g, 5.0 mmol) and *o*-toluoyl chloride (320 µL, 2.4 mmol) and the reaction mixture was purged with N_2 and then heated at 120 °C with stirring. After 15 h the reaction mixture was allowed to cool to rt and the mixture was diluted with EtOAc (25 mL) and filtered through a pad of Celite®. The filtrate was washed with 1M NaOH (aq.) (50 mL) then washed with H_2O (2 × 50 mL). The organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The product is then purified by silica flash column chromatography eluting with (EtOAc/hexane) (2/8) and afforded the title compound as a brown amorphous solid (28.6 mg, 7%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.20 (1H, ddd, *J* = 4.9, 1.4, 0.8 Hz, Ar*H*), 7.77 (1H, d, *J* = 0.8 Hz, Ar*H*), 7.75 (1H, s, Ar*H*), 7.63 (1H, dd, *J* = 8.3, 6.9 Hz, Ar*H*), 7.23 – 7.10 (5H, m, Ar*H*), 7.04 – 6.90 (5H, m, Ar*H*), 6.71 (1H, ddd, *J* = 7.5, 4.9, 1.4 Hz, Ar*H*), 2.41 (6H, s, 2 × C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.5 (2 × Ar*C*=O), 156.0 (Ar*C*), 148.9 (Ar*C*), 141.6 (Ar*C*H), 139.3 (Ar*C*), 139.0 (Ar*C*H), 137.4 (Ar*C*), 135.1 (Ar*C*), 131.5 (3 × Ar*C*H), 131.3 (2 × Ar*C*H), 131.1 (2 × Ar*C*H), 128.4 (Ar*C*), 125.1 (2 × Ar*C*H), 124.8 (Ar*C*), 121.8 (Ar*C*), 21.0 (2 × Ar*C*H$_3$); HRMs (ESI µTOF) m/z calculated for $C_{27}H_{21}NO_2$ $[M+H]^+$: 392.1651, found: 392.1673.

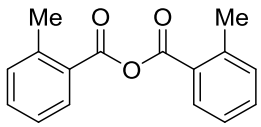
Mesityl(2-(pyridin-2-yl)phenyl)methanone (364a)[11]



To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (0.031 g, 0.05 mmol) and dry toluene (3 mL) and the solution was stirred under N_2. To this was added 2-phenylpyridine (140 µL, 1.0 mmol), tricyclohexylphosphine (0.030 g, 0.1 mmol), K_2CO_3 (0.68 g, 4.9 mmol) and 2,4,6-trimethylbenzoyl chloride (410 µL, 2.5 mmol) and the reaction mixture was purged with N_2 and then heated at 120 °C with stirring. After 15 h the reaction mixture was allowed to cool to rt and the mixture was diluted with EtOAc (25 mL) and filtered through a pad of Celite®. The filtrate was

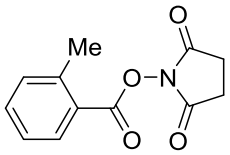
washed with 1M NaOH (aq.) (50 mL) then washed with H_2O (2 × 50 mL). The organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The product was then purified by silica flash column chromatography eluting with (EtOAc/hexane) (1/9) to afford the product as an oil (74.4 mg, 25%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.55 (1H, ddd, *J* = 4.9, 1.8, 1.1 Hz, Ar*H*), 7.65 (1H, td, *J* = 7.6, 1.8 Hz, Ar*H*), 7.58 – 7.47 (3H, m, Ar*H*), 7.45 – 7.37 (2H, m, Ar*H*), 7.17 (1H, ddd, *J* = 7.6, 4.9, 1.0 Hz, Ar*H*), 6.77 (2H, s, Ar*H*), 2.25 (3H, s, CH_3), 2.18 (6H, s, 2 × CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 200.4 (Ar*C*=O), 159.5 (Ar*C*N), 148.9 (Ar*C*H), 141.7 (Ar*C*), 139.1 (Ar*C*), 139.1 (Ar*C*), 136.9 (Ar*C*), 136.0 (Ar*C* & Ar*C*H), 131.9 (Ar*C*H), 131.1 (Ar*C*H), 130.8 (Ar*C*H), 128.9 (Ar*C*) 128.9 (2 × Ar*C*H), 128.6 (Ar*C*H), 123.3 (Ar*C*H), 121.9 (Ar*C*H), 21.2 (*C*H_3), 20.4 (2 × *C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{21}H_{19}NO$ $[M+H]^+$: 302.1545, found: 302.1551.

2-Methylbenzoic anhydride (362)



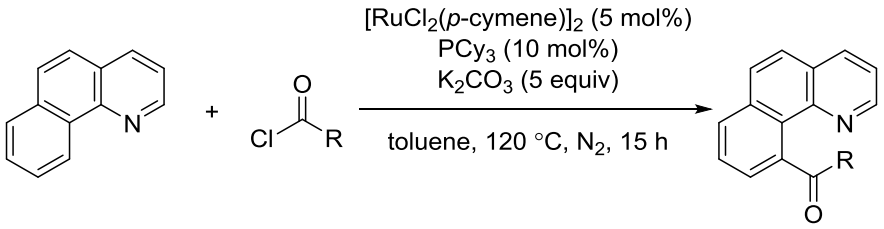
Pyrdine (10 mL, 123.6 mmol) was added portionwise to *o*-toluoyl chloride (4 mL, 30.7 mmol) under N_2 and allowed the solution to stir at rt overnight. The reaction mixture was quenched with ice cold water (200 mL). A solid precipitate was formed and filtered under vacuum and then washed with ice cold water (100 mL) and dried under high vacuum in a dessicator over P_2O_5. The title compound was obtained as a white crystalline solid (3.47 g, 44%); mpt. 42 – 49 °C, (lit.[12] 37 – 39 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (2H, dd, *J* = 7.7, 1.4 Hz, Ar*H*), 7.51 (2H, td, *J* = 7.7, 1.4 Hz, Ar*H*), 7.36 – 7.29 (4H, m, Ar*H*), 2.71 (6H, s, ArCH_3); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.1 (2 × Ar*C*=O), 142.7 (2 × Ar*C*Me), 133.7 (2 × Ar*C*H), 132.4 (2 × Ar*C*H), 131.6 (2 × Ar*C*H), 127.9 (2 × Ar*C*), 126.2 (2 × Ar*C*H), 22.1 (2 × Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{16}H_{14}O_3$ $[M+Na]^+$: 277.0841, found: 277.0845.

2,5-Dioxopyrrolidin-1-yl 2-methylbenzoate (363)[13]



To a solution of *N*-hydroxysuccinimide (0.76 g, 6.6 mmol) in THF (10 mL), was added triethylamine (0.84 mL, 6.0 mmol) followed by dropwise addition of *o*-toluoyl chloride (0.78 mL, 6.0 mmol). The mixture was stirred under an atmosphere of N_2 for 2 h at rt. The solvent was removed *in vacuo* and the residue was taken up in dichloromethane (15 mL) and washed with water (3 × 25 mL) and dried over $MgSO_4$, filtered then concentrated *in vacuo* to afford the title compound as a white solid (1.39 g, quant.); mpt. 151 – 161 °C, (Lit.[14] 145 – 146 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.14 – 8.10 (1H, m, Ar*H*), 7.52 (1H, td, *J* = 7.6, 1.2 Hz, Ar*H*), 7.33 – 7.30 (2H, m, Ar*H*), 2.91 (4H, br s, 2 × C*H*$_2$), 2.62 (3H, s, ArC*H*$_3$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.6 (2 × N*C*=O), 162.2 (Ar*C*=O), 142.3 (Ar*C*), 134.2 (Ar*C*H), 132.1 (Ar*C*H), 131.5 (Ar*C*H), 126.2 (Ar*C*H), 124.4 (Ar*C*), 25.9 (2 × *C*H$_2$), 21.8 (Ar*C*H$_3$); HRMS (ESI μTOF) m/z calcd for $C_{12}H_{11}NO_4$ $[M+Na]^+$: 256.0586, found: 256.0573.

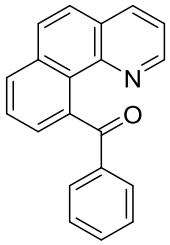
5.3.1. General Procedure IV



250 **357** (2.5 equiv) **358**

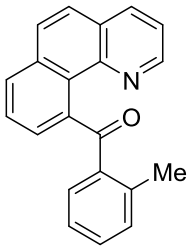
To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (0.05 mmol) and dry toluene (3 mL) and the solution was stirred under N_2. To this was added benzo[*h*]quinoline (1.00 mmol), tricyclohexylphosphine (0.1 mmol), K_2CO_3 (5.0 mmol) and the acyl chloride (2.5 mmol) and the reaction mixture was purged with N_2 and then heated at 120 °C with stirring. After 15 h the reaction mixture was allowed to cool to rt and the mixture was diluted with EtOAc (25 mL) and filtered through a pad of Celite®. The filtrate was washed with 1 M NaOH (aq.) (50 mL) then washed with H_2O (2 × 50 mL). The organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The product is then purified by silica flash column chromatography with the appropriate eluent system.

Benzo[*h*]quinolin-10-yl(phenyl)methanone (358a)[15]



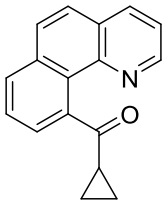
Benzo[*h*]quinoline (0.17 g, 1.0 mmol) and benzoyl chloride (280 µL, 2.4 mmol) were reacted under the general procedure IV and purified by flash column chromatography with dichloromethane (100%) to give the desired product as a yellow solid (28.7 mg, 10%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.50 (1H, dd, *J* = 4.4, 1.7 Hz, Ar*H*), 8.09 (1H, dd, *J* = 8.0, 1.7 Hz, Ar*H*), 8.04 (1H, dd, *J* = 8.0, 1.2 Hz, Ar*H*), 7.89 (1H, d, *J* = 8.8 Hz, Ar*H*), 7.81 – 7.75 (3H, m, Ar*H*), 7.73 (1H, d, *J* = 8.8 Hz, Ar*H*), 7.63 (1H, dd, *J* = 7.2, 1.4 Hz, Ar*H*), 7.41 (1H, app tt, *J* = 7.2, 1.4 Hz, Ar*H*), 7.34 – 7.27 (3H, m, Ar*H*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.8 (Ar*C*=O), 147.2 (Ar*C*HN), 144.7 (Ar*C*N), 139.3 (Ar*C*), 139.0 (Ar*C*), 135.4 (Ar*C*H), 133.9 (Ar*C*), 131.8 (Ar*C*H), 129.3 (Ar*C*), 129.1 (Ar*C*H), 128.8 (2 × Ar*C*H), 128.2 (2 × Ar*C*H), 127.9 (Ar*C*H), 127.8 (Ar*C*H), 127.1 (Ar*C*), 126.5 (Ar*C*H), 126.2 (Ar*C*H), 121.8 (Ar*C*H); HRMS (ESI µTOF) m/z calcd for $C_{20}H_{13}NO$ $[M+H]^+$: 284.1075, found: 284.1086.

Benzo[*h*]quinolin-10-yl(*o*-tolyl)methanone (358b)[10]



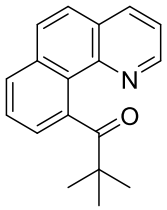
Benzo[*h*]quinoline (0.17 g, 1.0 mmol) and o-toluoyl chloride (320 µL, 2.5 mmol) were reacted under the general procedure IV and purified by flash column chromatography with (EtOAc/hexane) (2/8) to give the desired product as a pink crystalline solid (98.2 mg, 34%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.58 – 8.52 (2H, m, Ar*H*), 8.11 (1H, dd, *J* = 8.1, 1.8 Hz, Ar*H*), 7.90 – 7.84 (2H, m, Ar*H*), 7.74 (1H, t, *J* = 7.7 Hz, Ar*H*), 7.70 (1H, d, *J* = 8.8 Hz, Ar*H*), 7.57 – 7.50 (2H, m, Ar*H*), 7.44 (1H, d, *J* = 7.7 Hz, Ar*H*), 7.39 (2H, m, Ar*H*), 2.72 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.3 (Ar*C*=O), 149.1 (Ar*C*N), 148.1 (Ar*C*HN), 145.7 (Ar*C*), 141.0 (Ar*C*), 136.2 (Ar*C*), 135.6 (Ar*C*H), 132.1 (Ar*C*H), 132.0 (Ar*C*H), 131.7 (Ar*C*), 130.3 (Ar*C*H), 128.3 (Ar*C*H), 128.1 (Ar*C*H), 127.2 (Ar*C*), 126.8 (Ar*C*H), 126.5 (Ar*C*H), 125.9 (Ar*C*H), 123.6 (Ar*C*), 122.6 (Ar*C*H), 121.6 (Ar*C*H), 21.8 (ArCH_3); HRMS (ESI µTOF) m/z calcd for $C_{21}H_{15}NO$ $[M+H]^+$: 298.1232, found: 298.1230.

Benzo[*h*]quinolin-10-yl(cyclopropyl)methanone (358g)



Benzo[*h*]quinoline (0.17 g, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) were reacted under the general procedure IV and purified by flash column chromatography twice with column 1 (EtOAc/hexane) (3/7) and column 2 (dichloromethane/hexane) (75/25) to give the desired product as a white solid (82.4 g, 34%); ν_{max} (neat) / cm^{-1}; 3053, 3002, 1678, 1618, 1587, 1509,1493, 14340, 1421; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.91 (1H, dd, *J* = 4.4, 1.7 Hz, Ar*H*), 8.19 (1H, dd, *J* = 8.1, 1.7 Hz, Ar*H*), 7.97 (1H, dd, *J* = 8.1, 1.1 Hz, Ar*H*), 7.86 (1H, d, *J* = 8.8 Hz, Ar*H*), 7.77 – 7.68 (2H, m, Ar*H*), 7.54 – 7.48 (2H, m, Ar*H*), 2.19 (1H, tt, *J* = 7.9, 4.8 Hz, C*H*), 1.66 (1H, br s, C*H*), 1.27 – 0.83 (3H, m, CH_2, C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 209.1 (Ar*C*=O), 147.7 (Ar*C*HN), 145.2 (Ar*C*N), 141.7 (Ar*C*), 135.5 (Ar*C*H), 133.9 (Ar*C*), 129.0 (Ar*C*H), 128.1 (Ar*C*H), 128.0 (Ar*C*H), 127.9 (Ar*C*H), 127.0 (Ar*C*), 126.0 (Ar*C*H), 125.4 (Ar*C*H), 122.0 (Ar*C*H), 23.7 (*C*H), 11.7 (2 x CH_2);HRMS (ESI µTOF) m/z calcd for $C_{17}H_{13}NO$ $[M+Na]^+$: 270.0895, found: 270.0891.

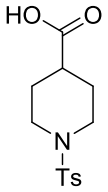
1-(Benzo[*h*]quinolin-10-yl)-2,2-dimethylpropan-1-one (358h)



Benzo[*h*]quinoline (0.18 mg, 1.0 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) were reacted under the general procedure IV and purified by flash column chromatography with (EtOAc/hexane) (3/7) to give the desired product as a brown solid (22.2 mg, 9%); ν_{max} (neat) / cm^{-1}; 2962, 2927, 1671, 1621, 1588, 1492, 1475, 1461, 1444, 1422; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.88 (1H, dd, *J* = 4.4, 1.7 Hz, Ar*H*), 8.18 (1H, dd, *J* = 8.0, 1.7 Hz, Ar*H*), 7.94 (1H, dd, *J* = 8.0, 1.2 Hz, Ar*H*), 7.85 (1H, d, *J* = 8.8 Hz, Ar*H*), 7.75 – 7.67 (2H, m, Ar*H*), 7.51 (1H, dd, *J* = 8.0, 4.4 Hz, Ar*H*), 7.44 (1H, dd, *J* = 7.2, 1.2 Hz, Ar*H*), 1.32 (9H, s, C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 216.3 (Ar*C*=O), 147.5 (Ar*C*HN), 145.2 (Ar*C*N), 140.2 (Ar*C*), 135.8 (Ar*C*H), 133.9 (Ar*C*), 128.8 (Ar*C*), 128.3 (Ar*C*H), 128.2

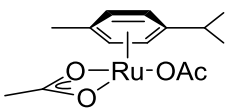
(Ar*C*H), 127.7 (Ar*C*H), 127.0 (Ar*C*), 125.9 (Ar*C*H), 124.6 (Ar*C*H), 122.0 (Ar*C*H), 45.5 (*C*$(CH_3)_3$), 27.8 (C(*C*$H_3)_3$); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{17}NO$ $[M+Na]^+$: 286.1208, found: 286.1215.

1-Tosylpiperidine-4-carboxylic acid[16]



To a solution of piperidine-4-carboxylic acid (1.51 g, 11.7 mmol), NaOH (0.96 g, 24.0 mmol) in Et_2O:H_2O (1:1) (25 mL) was added *p*-toluenesulfonyl chloride (2.22 g, 11.6 mmol) and the mixture was stirred until a white precipitate is formed. The mixture was diluted with Et_2O (15 mL) and H_2O (15 mL) to give a biphasic mixture. The pH of the aqueous layer was adjusted to pH3 by addition of 4M HCl (aq). The precipitate was filtered and dissolved in EtOAc (25 mL). The solution was dried over $MgSO_4$ and concentrated under reduced pressure and afforded the crude compound without need for further purification as a white fluffy solid (2.77 g, 84%); mp 168 – 170 °C (lit.[17] 169 – 171 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.63 (2H, d, *J* = 8.2 Hz, Ar*H*), 7.32 (2H, d, *J* = 8.2 Hz, Ar*H*), 3.65 (2H, dt, *J* = 7.4, 3.5 Hz, C*H*2), 2.50 – 2.37 (2H, m, C*H*), 2.44 (3H, s, ArCH_3), 2.28 (1H, tt, *J* = 15.0, 6.1 Hz, C*H*$(CH_2)_2$), 2.05 – 1.93 (2H, m, C*H*), 1.90 – 1.73 (2H, m, C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.31 (Ar*C*=O), 143.8 (Ar*C*Me), 133.1 (Ar*C*), 129.9 (2 × Ar*C*H), 127.8 (2 × Ar*C*H), 45.5 (2 x N*C*H2), 39.8 (*C*HC(O)), 27.3 (2 × *C*H_2), 21.7 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{13}H_{17}NSO_4$ [M-H]: 282.0795, found: 282.0804.

[Ruthenium bisacetate (*p*-cymene)] (368)[18]

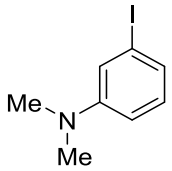


To an oven dried flask was added $[RuCl_2(p\text{-cymene})]_2$ (0.18 g, 0.3 mmol) and $Ag(OAc)_2$ (0.11 g, 0.7 mmol) in dry dichloromethane (25 mL) and was purged with N_2. The reaction mixture was stirred at rt under an atmosphere of N_2. After 3 h, the solvent was removed under reduced pressure and the residue was recrystallised from (dichloromethane/hexane) (1:1, v/v) to give the title compound as a bright orange crystals (73 mg, 36%); ^{1}H NMR (400 MHz, CD_3CN) δ 5.80 (2H, d, *J* = 6.0 Hz, 2 × ArH), 5.56 (2H, d, *J* = 6.0 Hz, 2 × ArH), 2.77 (1H, hept, *J* = 6.8 Hz, C*H*), 2.15 (3H, s, CH_3),

1.76 (6H, s, 2 × CH_3), 1.31 (3H, s, CHMeCH_3), 1.29 (3H, s, CHMeCH_3); ^{13}C NMR (100 MHz, CD_3CN) δ 183.8 (2 × *C*=O), 98.3 (Ar*C*), 93.6 (Ar*C*), 79.9 (2 × Ar*C*H), 78.3 (2 × Ar*C*H), 32.2 (2 × C(O)*C*H_3), 23.8 (*C*H), 22.6 (2 × CH*C*H_3), 18.7 (Ar*C*H_3).

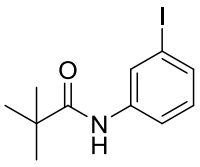
Preparation of aryl iodides

3-Iodo-*N,N*-dimethylaniline[19]



To a solution of 3-iodoaniline (1.04 g, 4.8 mmol) in acetonitrile (20 mL) was added 37% wt aqueous formaldehyde (4 mL, 145.2 mmol) and sodium cyanoborohydride (0.95 g, 15.17 mmol) with stirring at rt. Acetic acid (0.5 mL, 8.7 mmol) was added and the mixture allowed to stir at rt for 3 h. An additional portion of acetic acid (0.5 mL) was added and stirring was continued for 30 min. Et_2O (75 mL) was added into the reaction mixture and then washed with 1M KOH (aq.) (2 × 20 mL), dried over K_2CO_3 and the solvent was removed under reduced pressure to give the product as a dark brown oil without need for further purification (1.17 g, quant.); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.94 – 6.88 (2H, m, Ar*H*), 6.80 (1H, t, *J* = 8.4 Hz, Ar*H*), 6.53 (1H, ddd, *J* = 8.4, 2.4, 0.9 Hz, Ar*H*), 2.79 (6H, s, 2 × CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.5 (Ar*C*NMe_2), 130.4 (Ar*C*H), 125.2 (Ar*C*H), 121.0 (Ar*C*H), 111.6 (Ar*C*H), 95.7 (Ar*C*I), 40.4 (2 × *C*H_3); HRMS (ESI μTOF) m/z calcd for $C_8H_{10}NI$ $[M+H]^+$: 247.9931, found: 247.9924.

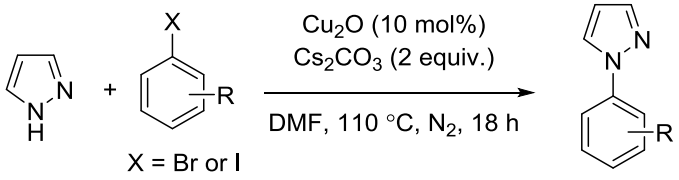
***N*-(3-Iodophenyl)pivalamide[20]**



To a solution of 3-iodoaniline (2 mL, 16.6 mmol) in dry dichloromethane (24 mL), trimethylacetyl chloride (3 mL, 24.3 mmol) and triethylamine (5 mL, 35.9 mmol) were added slowly at 0 °C and the mixture allowed to stir at 0 °C for 1.5 h. After this, TLC analysis showed the full consumption of the starting material. The reaction mixture was washed with water (100 mL), $NaHCO_3$ (sat.) (100 mL) and brine (sat.) (100 mL). The organics were dried over $MgSO_4$, filtered and concentrated

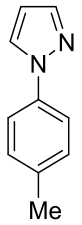
under reduced pressure to give a brown solid without the need for further purification (5.04 g, quant.); mpt. 142 – 150 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.97 (1H, t, *J* = 1.9 Hz, Ar*H*), 7.49 (1H, ddd, *J* = 8.0, 1.9, 0.9 Hz, Ar*H*), 7.43 (1H, ddd, *J* = 8.0, 1.9, 0.9 Hz, Ar*H*), 7.03 (1H, t, *J* = 8.0 Hz, Ar*H*), 1.31 (9H, s, C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.7 (^{t}Bu*C*=ONH), 139.3 (Ar*C*NH), 133.3 (Ar*C*H), 130.5 (Ar*C*H), 128.8 (Ar*C*H), 119.2 (Ar*C*H), 94.2 (Ar*C*I), 39.8 (*C*(CH$_3$)$_3$), 27.7 (C(*C*H$_3$)$_3$); HRMS (ESI μTOF) m/z calcd for $C_{11}H_{14}INO$ $[M+Na]^+$: 326.0018, found: 326.0006.

5.3.2. General Procedure V for synthesising 1-phenyl pyrazole derivatives[21]



To an oven-dried flask was added Cu_2O (1.03 mmol), Cs_2CO_3 (20.3 mmol) and pyrazole (10.0 mmol). Under a nitrogen atmosphere, aryl halide (15.2 mmol) was added followed by anhydrous DMF (17 mL). The flask was sealed under an atmosphere of nitrogen and heated up to 110 °C and refluxed with stirring. After 20 h, the reaction mixture was cooled to rt and diluted with dichloromethane (50 mL). The resulting solution was filtered through a pad of silica gel and the solvent was removed under reduced pressure. The residue was then diluted with EtOAc (25 mL) and washed with water (2 × 50 mL), and the organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The crude residue was purified by silica flash column chromatography eluting with (EtOAc/ hexane) (1/9).

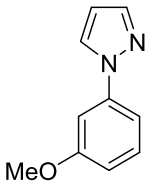
1-(*p*-Tolyl)-1*H*-pyrazole (334a)[22]



Following General Procedure V (using 12.5 mmol scale), 4-iodotoluene (4.15 g, 19.1 mmol) in anhydrous DMF (20 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane (1/9)to give the desired product as a pale yellow solid (1.32 g, 66%); mpt. 33 – 40 °C (Lit.[22] 30 – 31 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.85 (1H, dd, *J* = 2.1, 0.3 Hz, Ar*H*), 7.71 (1H, app d, *J* = 2.1 Hz, Ar*H*), 7.57 (2H, m, Ar*H*), 7.22 (2H, d, *J* = 8.1 Hz, Ar*H*), 6.42 (1H, dd, *J* = 2.1, 0.3 Hz,

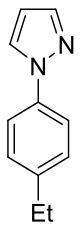
Ar*H*), 2.36 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 140.7 (Ar*C*H), 138.0 (Ar*C*N), 136.2 (Ar*C*), 129.9 (2 × Ar*C*H), 126.7 (Ar*C*H), 119.1 (2 × Ar*C*H), 107.3 (Ar*C*H), 20.9 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{10}H_{10}N_2$ $[M+H]^+$: 159.0922, found: 159.0921.

1-(3-Methoxyphenyl)-1*H*-pyrazole (334b)[23]



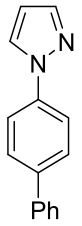
Following General Procedure V (using 2.5 mmol scale), 3-iodoanisole (450 µL, 3.8 mmol) in anhydrous DMF (6 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a colourless oil (389 mg, 90%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.92 (1H, dd, *J* = 1.9 , 0.5 Hz, Ar*H*), 7.72 (1H, app d, *J* = 1.9 Hz, Ar*H*), 7.37 – 7.30 (2H, m, Ar*H*), 7.23 (1H, ddd, *J* = 8.1, 2.3, 0.9 Hz, Ar*H*), 6.83 (1H, ddd, *J* = 8.1, 2.3, 0.9 Hz, Ar*H*), 6.46 (1H, dd, *J* = 1.9, 0.5 Hz, Ar*H*), 3.87 (3H, s, OCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 160.6 (Ar*C*OMe), 141.4 (Ar*C*N), 141.1 (Ar*C*H), 130.3 (Ar*C*H), 127.0 (Ar*C*H), 112.5 (Ar*C*H), 111.3 (Ar*C*H), 107.7 (Ar*C*H), 105.2 (Ar*C*H), 55.6 (O*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{10}H_{10}N_2O$ $[M+H]^+$: 175.0871, found: 175.0877.

1-(4-Ethylphenyl)-1*H*-pyrazole (381a)[24]



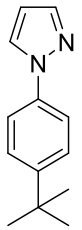
Following General Procedure V, 1-bromo-4-ethylbenzene (2.1 mL, 15.2 mmol) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a white solid (977 mg, 56%); mpt. 36 – 41 °C (Lit. oil); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.89 (1H, app d, *J* = 1.9 Hz, Ar*H*), 7.72 (1H, app d, *J* = 1.9 Hz, Ar*H*), 7.60 (2H, d, *J* = 8.6 Hz, Ar*H*), 7.27 (2H, d, *J* = 8.6 Hz, Ar*H*), 6.45 (1H, t, *J* = 1.9 Hz, Ar*H*), 2.68 (2H, q, *J* = 7.7 Hz, CH_2CH$_3$), 1.26 (3H, t, *J* = 7.7 Hz, CH_2CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.8 (Ar*C*Et), 140.9 (Ar*C*H), 138.2 (Ar*C*N), 128.9 (2 × Ar*C*H), 126.9 (Ar*C*H), 119.4 (2 × Ar*C*H), 107.4 (Ar*C*H), 28.5 (Ar*C*H_2), 15.7 (CH_2*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{11}H_{12}N_2$ $[M+H]^+$: 173.1079, found: 173.1083.

1-([1,1'-Biphenyl]-4-yl)-1*H*-pyrazole (381b)[25]



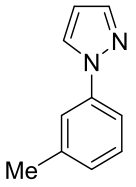
Following General Procedure V (using 7.9 mmol scale), 4-bromobiphenyl (2.78 g, 11.9 mmol) in anhydrous DMF (17 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (1.07 g, 65%); mpt. 119 – 131 °C (Lit.[25] 134 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.97 (1H, d, *J* = 2.1 Hz, Ar*H*), 7.81 – 7.74 (3H, m, Ar*H*), 7.7 – 7.61 (4H, m, Ar*H*), 7.49 – 7.43 (2H, m, Ar*H*), 7.39 – 7.34 (1H, m, Ar*H*), 6.50 (1H, t, *J* = 2.1 Hz, Ar*H*); ^{13}C NMR (75 MHz, CDCl3) δ 141.3 (Ar*C*H), 140.2 (Ar*C*), 139.5 (Ar*C*), 129.0 (2 × Ar*C*H), 128.2 (2 × Ar*C*H), 127.6 (Ar*C*H), 127.1 (2 × Ar*C*H), 126.9 (Ar*C*H), 119.6 (2 × Ar*C*H), 107.8 (Ar*C*H); HRMS (ESI μTOF) m/z calcd for $C_{15}H_{12}N_2$ $[M+H]^+$: 221.1079, found: 221.1054.

1-(4-(*tert*-Butyl)phenyl)-1*H*-pyrazole (381c)[24]



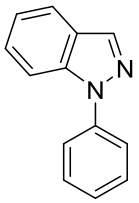
Following General Procedure V, 1-bromo-4-*tert*-butylbenzene (2.6 mL, 15.0 mmol) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a colourless oil (1.02 g, 51%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.90 (1H, d, *J* = 2.0 Hz, Ar*H*), 7.72 (1H, d, *J* = 2.0 Hz, Ar*H*), 7.63 – 7.60 (2H, m, Ar*H*), 7.48-7.45 (2H, m, Ar*H*), 6.45 (1H, t, *J* = 2.0 Hz, Ar*H*), 1.35 (9H, s, C(CH_3)); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.7 (Ar*C*^{t}Bu), 140.9 (Ar*C*H), 137.9 (Ar*C*N), 126.8 (Ar*C*H), 126.4 (2 × Ar*C*H), 119.1 (2 × Ar*C*H), 107.4 (Ar*C*H), 34.7 (*C*$(CH_3)_3$), 31.5 (C(*C*$H_3)_3$); HRMS (ESI μTOF) m/z calcd for $C_{13}H_{16}N_2$ $[M+H]^+$: 201.1392, found: 201.1391.

1-(*m*-Tolyl)-1*H*-pyrazole (381d)[21]



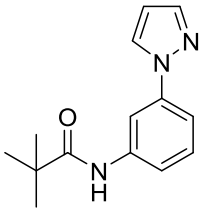
Following General Procedure V (using 9.5 mmol scale), 3-iodotoluene (1.95 mL, 14.4 mmol) in anhydrous DMF (20 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a colourless oil (1.38 g, 87%); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (1H, app d, *J* = 2.0 Hz, Ar*H*), 7.72 (1H, app s, Ar*H*), 7.55 (1H, s, Ar*H*), 7.46 (1H, d, *J* = 7.7 Hz, Ar*H*), 7.30 (1H, t, *J* = 7.7 Hz, Ar*H*), 7.07 (1H, d, *J* = 7.7 Hz, Ar*H*), 6.42 (1H, t, *J* = 2.0 Hz, Ar*H*), 2.39 (3H, s, ArCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 140.8 (Ar*C*H), 140.1 (Ar*C*Me), 139.4 (Ar*C*N), 129.1 (Ar*C*H), 127.1 (Ar*C*H), 126.7 (Ar*C*H), 119.9 (Ar*C*H), 116.1 (Ar*C*H), 107.4 (Ar*C*H), 21.4 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{10}H_{10}N_2$ $[M+H]^+$: 159.0922, found: 159.0927.

1-Phenyl-1*H*-indazole (381e)[26]



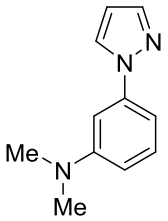
Following General Procedure V (using 5.1 mmol scale), indazole (0.61 g, 5.1 mmol) and iodobenzene (860 µL, 7.7 mmol) in anhydrous DMF (15 mL) were reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a pale yellow solid (280 mg, 28%); mpt. 85 – 92 °C (Lit.[26] 76 – 78 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.25 (1H, d, *J* = 0.5 Hz, Ar*H*), 7.86 – 7.73 (4H, m, Ar*H*), 7.61 – 7.50 (2H, m, Ar*H*), 7.48 – 7.33 (2H, m, Ar*H*), 7.27 – 7.22 (1H, m, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 140.2 (Ar*C*N), 138.7 (Ar*C*), 135.4 (Ar*C*H), 129.4 (2 × Ar*C*H), 127.1 (Ar*C*H), 126.6 (Ar*C*H), 125.3 (Ar*C*), 122.7 (2 × Ar*C*H), 121.5 (Ar*C*H), 121.3 (Ar*C*H), 110.4 (Ar*C*H); HRMS (ESI µTOF) m/z calcd for $C_{13}H_{10}N_2$ $[M+H]^+$: 195.0922, found: 195.0921.

***N*-(3-(1*H*-Pyrazol-1-yl)phenyl)pivalamide (381f)**



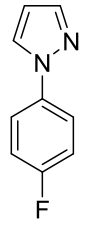
Following General Procedure V (using 8.2 mmol scale), *N*-(3-iodophenyl)pivalamide (3.74 g, 12.4 mmol) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a white solid (652 mg, 33%); mpt 134 – 137 °C; ν_{max} (neat) / cm^{-1}; 3296, 2963, 1654, 1601, 1539, 1516, 1435; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.98 (1H, t, *J* = 1.8 Hz, Ar*H*), 7.96 (1H, d, *J* = 2.0 Hz, Ar*H*), 7.71 (1H, d, *J* = 2.0 Hz, Ar*H*), 7.50 (1H, dt, *J* = 7.5, 1.8 Hz, Ar*H*), 7.46 – 7.35 (3H, m, Ar*H*), 6.46 (1H, t, *J* = 2.0 Hz, Ar*H*), 1.33 (9H, s, C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.9 (*C*=ONH), 141.3 (Ar*C*H), 140.8 (Ar*C*N), 139.3 (Ar*C*NH), 130.1 (Ar*C*H), 127.0 (Ar*C*H), 117.6 (Ar*C*H), 114.6 (Ar*C*H), 110.7 (Ar*C*H), 107.8 (Ar*C*H), 39.9 (*C*(CH_3)$_3$), 27.7 (C(*C*H_3)$_3$); HRMS (ESI μTOF) m/z calcd for $C_{14}H_{17}N_3O$ [M+Na]$^+$: 266.1269, found: 266.1269.

_N,N_-Dimethyl-3-(1_H_-pyrazol-1-yl)aniline (381g)



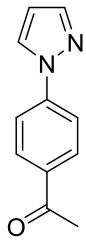
Following General Procedure V (using 2.1 mmol), 3-iodo-*N,N*-dimethylaniline (0.81 g, 3.3 mmol) in anhydrous DMF (3 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a yellow oil (349 mg, 88%); ν_{max} (neat) / cm^{-1}; 2886, 2806, 1605, 1579, 1518, 1441; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.89 (1H, dd, *J* = 2.4, 1.2 Hz, Ar*H*), 7.72 (1H, app d, *J* = 1.2 Hz, Ar*H*), 7.25 (1H, t, *J* = 8.1 Hz, Ar*H*), 7.14 (1H, t, *J* = 2.2 Hz, Ar*H*), 6.93 (1H, ddd, *J* = 8.1, 2.2, 0.6 Hz, Ar*H*), 6.61 (1H, ddd, *J* = 8.1, 2.2, 0.6 Hz, Ar*H*), 6.41 (1H, dd, *J* = 2.4, 1.2 Hz, Ar*H*), 2.96 (6H, s, N(CH_3)$_2$);^{13}C NMR (75 MHz, $CDCl_3$) δ 151.2 (Ar*C*NMe_2), 141.0 (Ar*C*N), 140.5 (Ar*C*H), 129.6 (Ar*C*H), 126.8 (Ar*C*H), 110.4 (Ar*C*H), 107.0 (Ar*C*H), 106.7 (Ar*C*H), 103.3 (Ar*C*H), 40.3 (N(*C*H_3)$_2$); HRMS (ESI μTOF) m/z calcd for $C_{11}H_{13}N_3$ [M+H]$^+$: 210.1007, found: 210.1001

1-(4-Fluorophenyl)-1*H*-pyrazole (381h)[24]



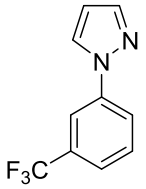
Following the general procedure V (using, 2.5 mmol scale), 4-fluoroiodobenzne (430 µL, 3.7 mmol) in anhydrous DMF (6 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a brown oil (387 mg, 95%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.85 (1H, d, *J* = 2.3 Hz, Ar*H*), 7.71 (1H, d, *J* = 1.6 Hz, Ar*H*), 7.68 – 7.60 (2H, m, Ar*H*), 7.18 – 7.09 (2H, m, Ar*H*), 6.45 (1H, t, *J* = 2.3 Hz, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.2 (d, *J* = 245.8 Hz, Ar*C*F), 141.2 (Ar*C*H), 136.6 (Ar*C*N), 127.0 (Ar*C*H), 121.1 (d, *J* = 8.3 Hz, 2 × Ar*C*H), 116.3 (d, *J* = 23.0 Hz, 2 × Ar*C*H), 107.8 (Ar*C*H); ^{19}F NMR (376 MHz, $CDCl_3$) δ -115.93 – -116.04 (m, ArCF); HRMS (ESI µTOF) m/z calcd for $C_9H_7N_2F$ $[M+H]^+$ m/z 163.067151, found m/z 163.0689.

1-(4-(1*H*-Pyrazol-1-yl)phenyl)ethan-1-one (381i)[27]



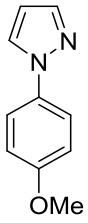
Following General Procedure V (using 8.0 mmol scale), 4-iodoacetophenone (3.99 g, 16.2 mmol) in anhydrous DMF (20 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a yellow solid (249 mg, 17%); mpt. 104 – 115 °C, (Lit.[27] 109 – 110 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.01 – 7.98 (1H, m, Ar*H*), 7.97 – 7.96 (2H, m, Ar*H*), 7.77 – 7.71 (2H, m, Ar*H*), 7.71 (1H, d, *J* = 1.7 Hz, Ar*H*), 6.45 (1H, dd, *J* = 2.5, 1.7 Hz, Ar*H*), 2.55 (3H, s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.8 (Ar*C*=O), 143.2 (Ar*C*), 142.0 (Ar*C*H), 134.6 (Ar*C*), 129.9 (Ar*C*H), 126.9 (Ar*C*H), 118.3 (Ar*C*H), 108.6 (Ar*C*H), 26.6 (*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{11}H_{10}N_2O$ $[M+Na]^+$: 209.069083, found: 209.0674.

1-(3-(Trifluoromethyl)phenyl)-1*H*-pyrazole (381j)[28]



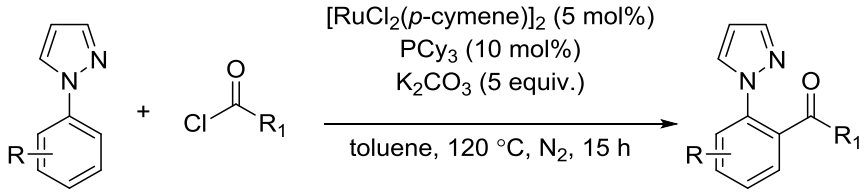
Following General Procedure V (using 7.1 mmol scale), 3-iodobenzotrifluoride (153 µL, 10.6 mmol) in anhydrous DMF (20 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a colourless oil (995 mg, 66%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.00 (1H, s, Ar*H*), 7.96 (1H, d, *J* = 2.4 Hz, Ar*H*), 7.90 – 7.84 (1H, m, Ar*H*), 7.75 (1H, d, *J* = 0.9 Hz, Ar*H*), 7.55 (2H, m, Ar*H*), 6.50 (1H, dd, *J* = 2.4, 0.9 Hz, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.9 (Ar*C*H), 140.6 (Ar*C*N), 132.1 (q, $J_{C\text{-}F}$ = 32.8 Hz, Ar*C*F_3), 130.2 (Ar*C*H), 126.9 (Ar*C*H), 125.6 (Ar*C*), 123.0 (q, $J_{C\text{-}F}$ = 3.8 Hz, Ar*C*H), 122.0 (Ar*C*H), 116.10 (q, $J_{C\text{-}F}$ = 3.9 Hz, Ar*C*H), 108.5 (Ar*C*H); ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.76 (CF_3); HRMS (ESI µTOF) m/z calcd for $C_{10}H_7N_2F_3$ $[M+H]^+$: 213.0634, found: 213.0647.

1-(4-Methoxyphenyl)-1*H*-pyrazole (381k)[23]



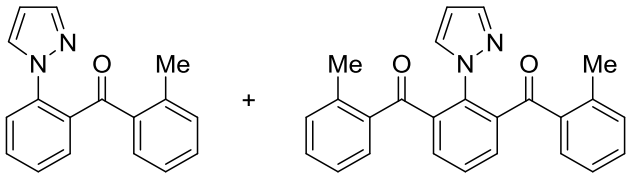
Following General Procedure V (using 1.0 mmol scale), 4-iodoanisole (0.35 g, 1.5 mmol) in anhydrous DMF (2 mL) was reacted and purified by flash column chromatography eluting with (EtOAc/hexane) (1/9) to give the desired product as a colourless oil (163 mg, 96%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.83 (1H, app d, *J* = 1.8 Hz, Ar*H*), 7.70 (1H, app d, *J* = 1.8 Hz, Ar*H*), 7.62 – 7.56 (2H, m, Ar*H*), 7.01 – 6.94 (2H, m, Ar*H*), 6.44 (1H, t, *J* = 1.8 Hz, Ar*H*), 3.84 (3H, s, O*CH*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.4 (Ar*C*OMe), 140.7 (Ar*C*H), 134.1 (Ar*C*N), 126.9 (2 × Ar*C*H), 121.1 (Ar*C*H), 114.7 (2 × Ar*C*H), 107.3 (Ar*C*H), 55.7 (O*CH*$_3$); HRMS (ESI µTOF) m/z calcd for $C_{10}H_{10}N_2O$ $[M+H]^+$: 175.0871, found: 175.0868.

5.3.3. General Procedure VI for ruthenium catalysed *ortho*-acylation reaction[29]



To an oven-dried carousel tube was added $[RuCl_2(p\text{-cymene})]_2$ (0.05 mmol) and dry toluene (3 mL) and the solution was stirred under N_2. To this was added phenyl pyrazole derivative (1.00 mmol), tricyclohexylphosphine (0.1 mmol), K_2CO_3 (5.0 mmol) and the acyl chloride (2.5 mmol) and the reaction mixture was purged with N_2 and then heated at 120 °C with stirring. After 15 h the reaction mixture was allowed to cool to rt and the mixture was diluted with EtOAc (25 mL) and filtered through a pad of Celite®. The filtrate was washed with 1 M NaOH (aq.) (50 mL) then washed with H_2O (2 × 50 mL). The organic material was dried over $MgSO_4$, filtered and concentrated *in vacuo*. The product is then purified by silica flash column chromatography with the appropriate eluent system.

(2-(1*H*-Pyrazol-1-yl)phenyl)(*o*-tolyl)methanone (365a and 365b)

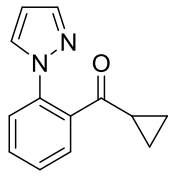


365a **365b**

To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and *o*-toluoyl chloride (320 µL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give a yellow oil which was an inseparable mixture of the product **365a** and the diacylated product **365b** (222 mg, conversion: **365a** = 79% and **365b** = 5%); ν_{max} (neat) / cm^{-1}; 3017, 1666, 1601, 1519; ^{1}H NMR (300 MHz, $CDCl_3$) (**365a**) δ 7.62 (1H, dd, *J* = 7.9, 1.8 Hz, Ar*H*), 7.57 – 7.51 (2H, m, Ar*H*), 7.47 – 7.44 (2H, m, Ar*H*), 7.37 (1H, d, *J* = 1.5 Hz, Ar*H*), 7.18 (1H, dd, *J* = 7.4, 1.5 Hz, Ar*H*), 7.13 – 7.05 (2H, m, Ar*H*), 6.94 (1H, t, *J* = 7.4 Hz, Ar*H*), 6.11(1H, t, *J* = 1.8 Hz, Ar*H*), 2.58 (3H, s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 197.1 (Ar*C*=O), 140.9 (Ar*C*H), 139.3 (Ar*C*), 138.9 (Ar*C*), 136.8 (Ar*C*), 135.5 (Ar*C*), 131.4 (Ar*C*H), 131.4 (Ar*C*H), 131.3 (Ar*C*H), 130.2 (Ar*C*H), 129.9 (Ar*C*H), 129.2 (Ar*C*H), 127.6 (Ar*C*H), 124.7 (Ar*C*H), 123.5 (Ar*C*H), 107.5

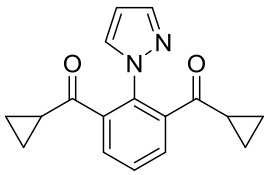
(Ar*C*H), 20.9 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{17}H_{14}N_2O$ $[M+Na]^+$: 285.1004, found: 285.1027.

(2-(1*H*-Pyrazol-1-yl)phenyl)(cyclopropyl)methanone (367a)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (103 mg, 50%); mpt. 64 – 79 °C; ν_{max} (neat) / cm^{-1}; 3071, 1670, 1603, 1582, 1520, 1496, 1456; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.70 (1H, app d, *J* = 1.6 Hz, Ar*H*), 7.67 (1H, app d, *J* = 2.4 Hz, Ar*H*), 7.58 – 7.47 (3H, m, Ar*H*), 7.45 – 7.37 (1H, m, Ar*H*), 6.44 (1H, t, *J*= 1.6 Hz, Ar*H*), 1.54 (1H, tt, *J* = 7.4, 3.9 Hz, C*H*(CH_2)$_2$), 1.09 (2H, dt, *J* = 7.4, 3.9 Hz, CH_2), 0.73 (2H, dt, *J* = 7.4, 3.9 Hz, CH_2); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.1 (Ar*C*=O), 141.5 (Ar*C*H), 138.6 (Ar*C*N), 136.4 (Ar*C*), 131.5 (Ar*C*H), 130.6 (Ar*C*H), 128.8 (Ar*C*H), 128.0 (Ar*C*H), 124.8 (Ar*C*H), 107.8 (Ar*C*H), 20.9 (*C*H), 12.8 (2 × *C*H_2); HRMS (ESI µTOF) m/z calcd for $C_{13}H_{12}N_2O$ $[M+H]^+$: 213.1028, found: 213.1036.

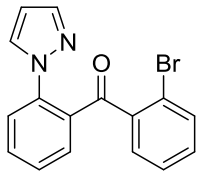
(2-(1*H*-Pyrazol-1-yl)-1,3-phenylene)bis(cyclopropylmethanone) (367b)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as an orange crystalline solid (74.4 mg, 27%); mpt. 80 – 86 °C; ν_{max} (neat) / cm^{-1}; 3077, 3009, 1671,1589, 1516; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.70 (1H, app d, *J* = 2.1 Hz, Ar*H*), 7.67 (1H, app d, *J* = 1.0 Hz, Ar*H*), 7.65 (1H, s, Ar*H*), 7.61 (1H, d, *J* = 1.9 Hz, Ar*H*), 7.54 (1H, dd, *J* = 6.9, 1.9 Hz, Ar*H*), 6.46 (1H, t, *J*= 2.1 Hz, Ar*H*), 1.52 (2H, tt, *J* = 7.6, 4.0 Hz, 2 × C*H*), 1.05 (4H, dt, *J* = 7.6, 4.0, 2 × CH_2), 0.72 (4H, dt, *J* = 7.6, 4.0 Hz, 2 × CH_2); ^{13}C NMR (75 MHz, $CDCl_3$) δ 203.6 (2 × Ar*C*=O), 141.8 (Ar*C*H), 138.7 (2 ×

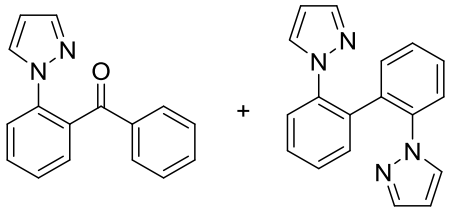
Ar*C*), 135.9 (Ar*C*), 132.9 (Ar*C*H), 130.7 (2 × Ar*C*H), 128.9 (Ar*C*H), 108.1 (Ar*C*H), 20.5 (2 × *C*H), 13.0 (4 × *C*H_2); HRMS (ESI μTOF) m/z calcd for $C_{17}H_{16}N_2O_2$ $[M+Na]^+$: 303.1109, found: 303.1130.

(2-(1*H*-Pyrazol-1-yl)phenyl)(2-bromophenyl)methanone (369a)



To a solution of 1-phenylpyrazole (130 μL, 1.0 mmol) and 2-bromobenzoyl chloride (320 μL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a yellow oil (93.1 mg, 29%); ν_{max} (neat) / cm^{-1}; 1734, 1675, 1601, 1586, 1519; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.73 (1H, dd, *J* = 7.8, 1.6 Hz, Ar*H*), 7.63 (1H, td, *J* = 7.7, 1.9 Hz, Ar*H*), 7.58 (1H, d, *J* = 1.9 Hz, Ar*H*), 7.52 – 7.41 (4H, m, Ar*H*), 7.24 – 7.20 (1H, m, Ar*H*), 7.15 – 7.08 (2H, m, Ar*H*), 6.12 (1H, t, *J* = 1.6 Hz, Ar*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 194.4 (Ar*C*=O), 141.4 (Ar*C*H), 139.4 (Ar*C*), 138.4 (Ar*C*), 134.0 (Ar*C*H & Ar*C*), 132.5 (Ar*C*H), 132.1 (Ar*C*H), 131.2 (Ar*C*H), 131.0 (Ar*C*H), 129.8 (Ar*C*H), 128.0 (Ar*C*H), 126.6 (Ar*C*H), 124.3 (Ar*C*H), 121.2 (Ar*C*Br), 107.7 (Ar*C*H); HRMS (ESI μTOF) m/z calcd for $C_{16}H_{11}{}^{79}BrN_2O$ $[M+Na]^+$: 348.9952, found: 348.9965.

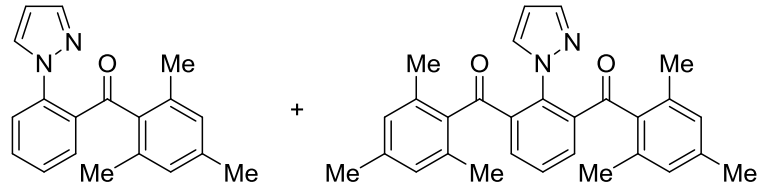
(2-(1*H*-Pyrazol-1-yl)phenyl)(phenyl)methanone (370a)



370a

To a solution of 1-phenylpyrazole (130 μL, 1.0 mmol) and benzoyl chloride (280 μL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give a yellow solid which was an inseparable mixture of the product and the phenylpyrazole dimer (104 mg, 24% conversion) ν_{max} (neat) / cm^{-1}; 3063, 1663, 1596, 1580, 1519, 1449; indistinguishable ^{1}H NMR and ^{13}C NMR data, see appendix for ^{1}H and ^{13}NMR spectra; HRMS (ESI μTOF) m/z calcd for $C_{16}H_{12}N_2O$ $[M+]^+$: 249.1028, found: 249.1029.

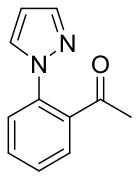
(2-(1*H*-Pyrazol-1-yl)phenyl)(mesityl)methanone (371a and 371b)



371a **371b**

To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and 2,4,6-trimethylbenzoyl chloride (410 µL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give a yellow oil which was an inseparable mixture of the product with the diacylated product (44.9 mg, conversion: **371a** = 12%, **371b** = 2%); ν_{max} (neat) / cm^{-1}; 2921, 1659, 1609, 1598, 1519; ^{1}H NMR (500 MHz, $CDCl_3$) (**371a**) δ 7.68 (1H, d, *J* = 1.7 Hz, Ar*H*), 7.62 – 7.61 (2H, m, Ar*H*), 7.55 (1H, dd, *J* = 7.8, 1.7 Hz, Ar*H*), 7.51 (1H, dd, *J* = 7.8, 1.1 Hz, Ar*H*), 7.44 (1H, td, *J* = 7.8, 1.1 Hz, Ar*H*), 6.79 (1H, s, Ar*H*), 6.75 (1H, s, Ar*H*), 6.35 (1H, t, *J* = 1.7 Hz, Ar*H*), 2.26 (3H, s, CH_3), 2.15 (3H, s, CH_3), 2.11 (3H, s, CH_3); ^{13}C NMR (125 MHz, $CDCl_3$) (**371a and 371b)** δ 198.4 (Ar*C*=O), 197.9 (Ar*C*=O), 140.6 (ArCH), 140.5 (ArCH), 139.9 (ArCH), 139.6 (ArCH), 139.3 (ArCH), 139.2 (ArCH), 136.1 (ArCH), 136.1 (ArCH), 135.8 (ArC), 133.8 (ArC), 133.0 (ArC), 132.8 (ArCH), 131.3 (ArCH), 129.7, 129.2 (ArCH), 129.1 (ArCH), 128.8 (ArCH), 127.3 (ArCH), 106.9 (ArCH), 106.1 (ArCH), 21.3 (Ar*C*H_3), 21.2 (Ar*C*H_3), 20.8 (Ar*C*H_3), 20.5 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{19}H_{18}N_2O$ $[M+H]^+$: 291.1498, found: 291.1502.

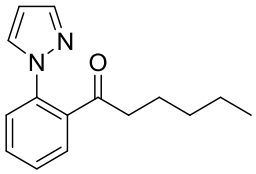
1-(2-(1*H*-Pyrazol-1-yl)phenyl)ethan-1-one (372a)[27]



On a 5 mmol scale reaction: To a solution of $[RuCl_2(p\text{-cymene})]$ (0.17 g, 0.3 mmol), PCy_3 (0.15 g, 0.5 mmol), K_2CO_3 (3.73 g, 27.0 mmol), 1-phenylpyrazole (0.71 mL, 5.4 mmol) and acetyl chloride (0.96 mL, 13.5 mmol) in dry toluene (10 mL) were reacted in a sealed Schlenk tube according to General Procedure VI, at 120 °C with stirring for 19 h and was purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a dark brown oil (406 mg, 41%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.74 (1H, app d, *J* = 2.4 Hz, Ar*H*), 7.72 (1H, app d, *J* =

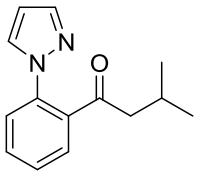
1.5 Hz, Ar*H*), 7.58 – 7.51 (2H, m, Ar*H*), 7.47 – 7.39 (2H, m, Ar*H*), 6.49 (1H, t, *J* = 2.4 Hz, Ar*H*), 1.98 (3H, s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.6 (Ar*C*=O), 141.7 (Ar*C*H), 138.3 (Ar*C*N), 136.4 (Ar*C*), 131.5 (Ar*C*H), 129.8 (Ar*C*H), 128.8 (Ar*C*H), 128.1 (Ar*C*H), 124.2 (Ar*C*H), 108.2 (Ar*C*H), 29.2 (*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{11}H_{10}N_2O$ $[M+H]^+$: 187.0871, found: 187.0881.

1-(2-(1*H*-Pyrazol-1-yl)phenyl)hexan-1-one (373a)



To a solution of 1-phenylpyrazole (130 μL, 1.0 mmol) and hexanoyl chloride (340 μL, 2.4 mmol) in dry toluene were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a brown oil (17.6 mg, 7%); ν_{max} (neat) / cm^{-1}; 2956, 2929, 1692, 1602, 1519, 1451; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.73 (1H, app d, *J* = 2.2 Hz, Ar*H*), 7.71 (1H, app d, *J* = 1.7 Hz, Ar*H*), 7.57 – 7.38 (4H, m, Ar*H*), 6.48 (1H, t, *J* = 2.2 Hz, Ar*H*), 2.17 (2H, t, *J* = 7.4 Hz, CH_2), 1.53 (2H, app tt, *J* = 7.5, 7.4 Hz, CH_2), 1.29 – 1.07 (4H, m, 2 × CH_2), 0.83 (3H, t, *J* = 6.9 Hz, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 205.0 (Ar*C*=O), 141.6 (Ar*C*H), 137.9 (Ar*C*N), 136.7 (Ar*C*), 131.1 (Ar*C*H), 129.8 (Ar*C*H), 128.6 (Ar*C*H), 128.0 (Ar*C*H), 123.9 (Ar*C*H), 108.1 (Ar*C*H), 42.2 (C(O)*C*H_2), 31.4 (*C*H_2), 24.1 (*C*H_2), 22.5 (*C*H_2), 14.0 (*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{15}H_{18}N_2O$ $[M+Na]^+$: 265.1317, found: 265.1335.

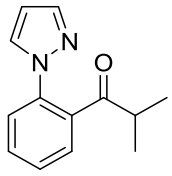
1-(2-(1*H*-Pyrazol-1-yl)phenyl)-3-methylbutan-1-one (374a)



To a solution of 1-phenylpyrazole (130 μL, 1.0 mmol) and isovaleryl chloride (300 μL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a brown oil (66.4 mg, 30%); ν_{max} (neat) / cm^{-1}; 2957, 1689, 1602, 1519; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.71 – 7.70 (2H, m, Ar*H*), 7.56 – 7.38 (4H, m, Ar*H*), 6.47 (1H, dd, *J* = 2.1, 2.4 Hz, Ar*H*), 2.07 – 1.97 (3H, m, CH_2 & *C*H(CH_3)$_2$), 0.81 – 0.79 (6H, m, 2 × CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.3 (Ar*C*=O), 141.5 (Ar*C*H),

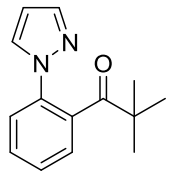
138.0 (Ar*C*N), 137.0 (Ar*C*), 131.1 (Ar*C*H), 130.0 (Ar*C*H), 128.6 (Ar*C*H), 128.1 (Ar*C*H), 124.2 (Ar*C*H), 108.0 (Ar*C*H), 51.0 (C(O)*C*H_2), 25.0 (*C*H(CH_3)$_2$), 22.6 (2 × *C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{14}H_{16}N_2O$ [M+Na]$^+$: 251.1160, found: 251.1170.

1-(2-(1*H*-Pyrazol-1-yl)phenyl)-2-methylpropan-1-one (375a)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and isobutyryl chloride (260 µL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a brown solid (117 mg, 56%); mpt. 52 – 75 °C; ν_{max} (neat) / cm^{-1}; 2967, 2935, 1682, 1602, 1580, 1520, 1451; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.74 (1H, app d, *J* = 2.3 Hz, Ar*H*), 7.68 (1H, app d, *J* = 1.6 Hz, Ar*H*), 7.54 – 7.34 (4H, m, Ar*H*), 6.45 (1H, t, *J* = 2.3 Hz, Ar*H*), 2.12 (1H, hept, *J* = 6.9 Hz, C*H*(CH_3)$_2$), 0.98 (3H, s, C*H*$_3$), 0.96 (3H, s, C*H*$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 209.2 Ar*C*=O), 141.5 (Ar*C*H), 137.6 (Ar*C*N), 135.4 (Ar*C*), 130.9 (Ar*C*H), 129.3 (Ar*C*H), 129.0 (Ar*C*H), 127.6 (Ar*C*H), 123.0 (Ar*C*H), 108.1 (Ar*C*H), 40.0 (*C*H), 18.7 (2 × *C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{13}H_{14}N_2O$ [M+H]$^+$: 215.1184, found: 215.1183.

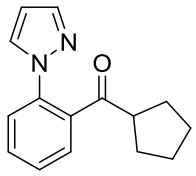
1-(2-(1*H*-Pyrazol-1-yl)phenyl)-2,2-dimethylpropan-1-one (376a)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure B and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a cream solid (118 mg, 53%); mpt. 82 – 94 °C; ν_{max} (neat) / cm^{-1}; 2973, 1684, 1675, 1604, 1582, 1519, 1501, 1479; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.75 (1H, dd, *J* = 2.3, 1.0 Hz, Ar*H*), 7.66 (1H, app d, *J* = 1.0 Hz, Ar*H*), 7.53 – 7.43 (2H, m, Ar*H*), 7.38 – 7.31 (1H, m, Ar*H*), 7.22 (1H, dd, *J* = 7.6, 1.0 Hz, Ar*H*), 6.43 (1H, dd, *J* = 2.3, 1.0 Hz, Ar*H*), 1.01 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.6 (Ar*C*=O), 141.2 (Ar*C*H), 136.6 (Ar*C*N), 135.1 (Ar*C*), 129.7 (Ar*C*H), 129.1 (Ar*C*H), 127.5 (Ar*C*H), 126.9 (Ar*C*H), 122.1

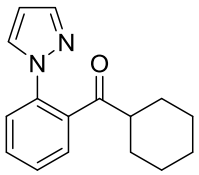
(Ar*C*H), 108.0 (Ar*C*H), 45.4 (*C*(CH_3)$_3$), 26.9 (C(*C*H_3)$_3$); HRMS (ESI μTOF) m/z calcd for $C_{14}H_{16}N_2O$ $[M+Na]^+$: 251.1160, found: 251.1154.

(2-(1*H*-Pyrazol-1-yl)phenyl)(cyclopentyl)methanone (377a)



to a solution of 1-phenylpyrazole (130 μL, 1.0 mmol) and cyclopentanecarbonyl chloride (300 μL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a yellow oil (13.3 g, 6%); ν_{max} (neat) / cm^{-1}; 2592, 2868, 1687, 1602, 1581, 1519, 1496, 1450; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.73 (1H, app d, *J* = 2.2 Hz, Ar*H*), 7.70 (1H, app d, *J* = 1.5 Hz, Ar*H*), 7.55 – 7.38 (4H, m, Ar*H*), 6.47 (1H, t, *J* = 2.2 Hz, Ar*H*), 2.49 (1H, app quint., *J* = 8.5, C*H*), 1.79 – 1.70 (2H, m, C*H*), 1.68 – 1.53 (4H, m, C*H*), 1.49 – 1.40 (2H, m, C*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 208.3 (Ar*C*=O), 141.6 (Ar*C*H), 137.8 (Ar*C*N), 136.5 (Ar*C*), 130.9 (Ar*C*H), 129.7 (Ar*C*H), 128.8 (Ar*C*H), 127.8 (Ar*C*H), 123.5 (Ar*C*H), 108.0 (Ar*C*H), 50.8 (*C*H), 30.0 (2 × *C*H_2), 26.2 (2 × *C*H_2); HRMS (ESI μTOF) m/z calcd for $C_{15}H_{16}N_2O$ $[M+Na]^+$: 263.1160, found: 263.1149.

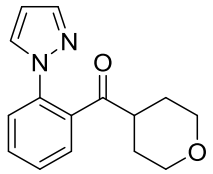
(2-(1*H*-Pyrazol-1-yl)phenyl)(cyclohexyl)methanone (378a)



To a solution of 1-phenylpyrazole (130 μL, 1.0 mmol) and cyclohexanecarbonyl chloride (330 μL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a brown oil (71.0 mg, 28%); ν_{max} (neat) / cm^{-1}; 2929, 2853, 1691, 1602, 1580, 1519, 1449; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.73 (1H, d, *J* = 2.4 Hz, Ar*H*), 7.70 (1H, d, *J* = 1.8 Hz, Ar*H*), 7.55 – 7.45 (2H, m, Ar*H*), 7.45 – 7.35 (2H, m, Ar*H*), 6.48 (1H, t, *J*= 2.4 Hz, Ar*H*), 1.80 (1H, tt, *J* = 10.9, 3.2 Hz, C*H*(CH_2)$_2$), 1.66 (4H, d, *J* = 10.9 Hz, C*H*), 1.57 – 1.51 (1H, m, C*H*), 1.37 – 1.22 (2H, m, C*H*), 1.19 – 0.91 (3H, m, C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 208.2 (Ar*C*=O), 141.5 (Ar*C*H), 137.7 (Ar*C*N), 135.8 (Ar*C*), 130.9

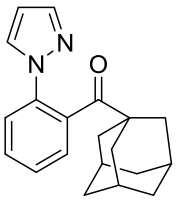
(Ar*C*H), 129.7 (Ar*C*H), 129.0 (Ar*C*H), 127.7 (Ar*C*H), 123.5 (Ar*C*H), 108.0 (Ar*C*H), 50.0 (*C*H(CH_2)$_2$), 29.0 (2 × *C*H_2), 25.9 (*C*H_2) , 25.8 (2 × *C*H_2); HRMS (ESI µTOF) m/z calcd for $C_{16}H_{18}N_2O$ [M+Na]$^+$: 277.1317, found: 277.1316.

(2-(1*H*-Pyrazol-1-yl)phenyl)(tetrahydro-2*H*-pyran-3-yl)methanone (379a)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and tetrahydro-2*H*-pyran-4-carbonyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a brown solid (25.1 mg, 9%); mpt. 70 – 81 °C; ν_{max} (neat) / cm^{-1}; 2954, 1691, 1603, 1581, 1520, 1499; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.77 (1H, app d, *J* = 2.5 Hz, Ar*H*), 7.68 (1H, app d, *J* = 1.5 Hz, Ar*H*), 7.56 – 7.49 (1H, m, Ar*H*), 7.46 (1H, d, *J* = 8.0 Hz, Ar*H*), 7.42 – 7.37 (2H, m, Ar*H*), 6.48 (1H, t, *J* = 2.5 Hz, Ar*H*), 3.87 (2H, ddd, *J* = 11.3, 4.0, 2.3 Hz, CH_2), 3.15 (2H, td, *J* = 11.3, 2.3 Hz, CH_2), 2.07 – 1.99 (1H, m, C*H*), 1.71 – 1.63 (2H, m, C*H*), 1.55 – 1.52 (2H, m, C*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 206.1 (Ar*C*=O), 141.5 (Ar*C*H), 137.6 (Ar*C*N), 134.9 (Ar*C*), 131.1 (Ar*C*H), 129.4 (Ar*C*H), 129.0 (Ar*C*H), 127.7 (Ar*C*H), 123.0 (Ar*C*H), 108.3 (ArCH), 67.3 (2 × O*C*H_2), 46.8 (*C*H), 28.7 (2 × *C*H_2); HRMS (ESI µTOF) m/z calcd for $C_{15}H_{16}N_2O_2$ [M+Na]$^+$: 279.1109, found: 279.1113.

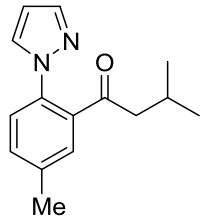
(2-(1*H*-Pyrazol-1-yl)phenyl)((3*r*,5*r*,7*r*)-adamantan-1-yl)methanone (380a)



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and 1-adamantanecarbonyl chloride (492 mg, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and was purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a light green crystalline solid (228 mg, 76%); mpt. 91 – 114 °C; ν_{max} (neat) / cm^{-1}; 2905, 2850, 1683, 1603, 1580, 1519, 1498, 1450; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.69 (1H, app d, *J* = 2.4 Hz, Ar*H*), 7.65 (1H, app d, *J* = 1.7 Hz, Ar*H*), 7.50 (1H, dd, *J* = 7.7, 1.2 Hz, Ar*H*), 7.43 (1H, td, *J* = 7.3, 1.2

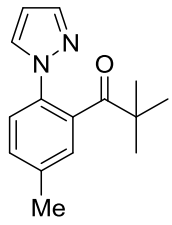
Hz, Ar*H*), 7.31 (1H, td, *J* = 7.3, 1.2 Hz, Ar*H*), 7.15 (1H, dd, *J* = 7.7, 1.2 Hz, Ar*H*), 6.39 (1H, t, *J* = 1.7 Hz, Ar*H*), 1.87 (3H, br s, C*H*), 1.61 – 1.50 (12H, m, C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 212.8 (Ar*C*=O), 141.0 (Ar*C*H), 136.5 (Ar*C*N), 134.7 (Ar*C*), 129.5 (Ar*C*H), 129.4 (Ar*C*H), 127.4 (Ar*C*H), 126.7 (Ar*C*H), 122.4 (Ar*C*H), 107.8 (Ar*C*H), 47.5 (C(O)*C*$(CH_2)_3$), 38.0 (3 × C(*C*$H_2)_3$), 36.4 (3 × *C*H), 27.9 (3 × *C*H); HRMS (ESI μTOF) m/z calcd for $C_{20}H_{22}N_2O$ $[M+H]^+$: 307.1810, found: 307.1818.

3-Methyl-1-(5-methyl-2-(1*H*-pyrazol-1-yl)phenyl)butan-1-one (382a)



To a solution of 1-(*p*-tolyl)-1*H*-pyrazole **334a** (0.15 g, 1.0 mmol) and isovaleryl chloride (300 μL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a pink oil (51.4 mg, 22%); ν_{max} (neat) / cm^{-1}; 2957, 2871, 1690, 1520, 1466; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.70 – 7.68 (1H, m, Ar*H*), 7.66 (1H, dd, *J* = 2.5, 0.5 Hz, Ar*H*), 7.33 – 7.32 (2H, m, Ar*H*), 7.29 – 7.28 (1H, m, Ar*H*), 6.46 (1H, dd, *J* = 2.5, 0.5 Hz, Ar*H*), 2.42 (3H, s, Ar*C*H_3), 2.03 – 2.02 (3H, m, CH_2 & C*H*), 0.81 – 0.78 (6H, m, 2 × CH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 204.6 (Ar*C*=O), 141.3 (Ar*C*H), 138.4 (Ar*C*N), 136.9 (Ar*C*Me), 135.7 (Ar*C*), 131.8 (Ar*C*H), 130.2 (Ar*C*H), 129.0 (Ar*C*H), 124.5 (Ar*C*H), 107.8 (Ar*C*H), 50.9 (*C*H2), 25.0 (*C*H), 22.6 (2 × *C*H_3), 21.1 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{15}H_{18}N_2O$ $[M+H]^+$: 243.1497, found: 243.1494.

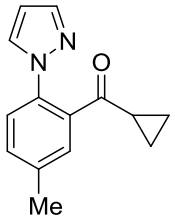
2,2-Dimethyl-1-(5-methyl-2-(1*H*-pyrazol-1-yl)phenyl)propan-1-one (383a)



To a solution of 1-(*p*-tolyl)-1*H*-pyrazole **334a** (0.15 g, 1.0 mmol) and trimethylacetyl chloride (300 μL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a white solid (145 mg, 60%); mpt. 71 – 78 °C; ν_{max} (neat) / cm^{-1}; 2972, 1690, 1585, 1515, 1480; ^{1}H

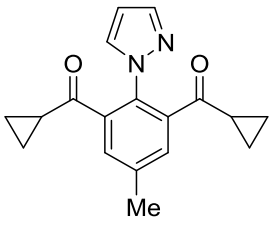
NMR (300 MHz, $CDCl_3$) δ 7.68 (1H, dd, *J* = 2.4, 1.3 Hz, Ar*H*), 7.62 (1H, app d, *J* = 1.3 Hz, Ar*H*), 7.36 (1H, d, *J* = 8.3 Hz, Ar*H*), 7.23 (1H, ddd, *J* = 8.3, 1.6, 0.5 Hz, Ar*H*), 6.98 (1H, dd, *J* = 1.6, 0.5 Hz, Ar*H*), 6.38 (1H, dd, *J* = 2.4, 1.3 Hz, Ar*H*), 2.37 (3H, s, ArCH_3), 0.97 (9H, s, C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.7 (Ar*C*=O), 140.8 (Ar*C*H), 136.8 (Ar*C*N), 134.9 (Ar*C*), 134.2 (Ar*C*), 130.2 (Ar*C*H), 129.0 (Ar*C*H), 127.7 (Ar*C*H), 122.0 (Ar*C*H), 107.6 (Ar*C*H), 45.2 (*C*(CH$_3$)$_3$), 26.8 (C(*C*H$_3$)$_3$), 21.0 (Ar*C*H3); HRMS (ESI µTOF) m/z calcd for $C_{15}H_{18}N_2O$ $[M+H]^+$: 243.1497, found: 243.1498.

Cyclopropyl(5-methyl-2-(1*H*-pyrazol-1-yl)phenyl)methanone (384a)



To a solution of 1-(*p*-tolyl)-1*H*-pyrazole **334a** (0.15 g, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a white solid (61.1 mg, 28%); mpt. 113 – 118 °C; ν_{max} (neat) / cm^{-1}; 3009, 1669, 1604, 1519, 1499, 1408; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.70 (1H, d, *J* = 1.6 Hz, Ar*H*), 7.64 (1H, d, *J* = 2.2 Hz, Ar*H*), 7.44 – 7.32 (3H, m, Ar*H*), 6.44 (1H, t, *J* = 2.2 Hz, Ar*H*), 2.42 (3H, s, ArCH_3), 1.54 (1H, tt, *J* = 7.5, 4.0 Hz, C*H*), 1.09 (2H, dt, *J* = 7.5, 4.0, CH_2), 0.73 (2H, dt, *J* = 7.5, 4.0 Hz, CH_2);^{13}C NMR (75 MHz, $CDCl_3$) δ 204.5 (Ar*C*=O), 141.3 (Ar*C*H), 138.3 (Ar*C*Me), 136.4 (Ar*C*N), 136.3 (Ar*C*), 132.2 (Ar*C*H), 130.8 (Ar*C*H), 129.1 (Ar*C*H), 125.0 (Ar*C*H), 107.6 (Ar*C*H), 21.1 (Ar*C*H$_3$), 20.9 (*C*H), 12.9 (2 × *C*H$_2$); HRMS (ESI µTOF) m/z calcd for $C_{14}H_{14}N_2O$ $[M+Na]^+$: 249.1004, found: 249.1002.

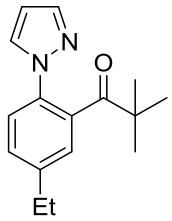
(5-Methyl-2-(1*H*-pyrazol-1-yl)-1,3-phenylene)bis(cyclopropylmethanone) (384b)



To a solution of 1-(*p*-tolyl)-1*H*-pyrazole **334a** (0.15 g, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the

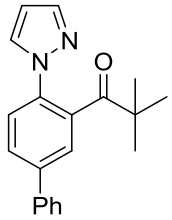
desired product as white crystalline needles (35.5 mg, 12%); mpt. 107 – 126 °C; ν_{max} (neat) / cm^{-1}; 3136, 1670, 1584, 1521, 1479, 1408; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.71 – 7.70 (1H, m, Ar*H*), 7.60 (1H, dd, *J* = 2.3, 0.5 Hz, Ar*H*), 7.48 (2H, app d, *J* = 0.6 Hz, Ar*H*), 6.46 (1H, dd, *J* = 2.3, 0.5 Hz, Ar*H*), 2.46 (3H, s, ArCH_3), 1.52 (2H, tt, *J* = 7.5, 4.0 Hz, 2 × C*H*), 1.06 (4H, dt, *J* = 7.5, 4.0 Hz, 2 × CH_2), 0.72 (4H, dt, *J* = 7.5, 4.0 Hz, 2 × CH_2); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.0 (2 × Ar*C*=O), 141.7 (Ar*C*H), 139.4 (Ar*C*Me), 138.7 (2 × Ar*C*), 133.8 (Ar*C*), 132.9 (Ar*C*H), 131.2 (2 × Ar*C*H), 108.0 (Ar*C*H), 21.1 (Ar*C*H_3), 20.5 (2 × *C*H), 13.1 (4 × *C*H_2); HRMS (ESI µTOF) m/z calcd for $C_{18}H_{18}N_2O_2$ $[M+Na]^+$ 317.1266, found: 317.1271.

1-(5-Ethyl-2-(1*H*-pyrazol-1-yl)phenyl)-2,2-dimethylpropan-1-one (385a)



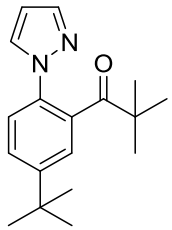
To a solution of 1-(4-ethylphenyl)-1*H*-pyrazole **381a** (0.17 g, 1.0 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as an orange oil (165 mg, 67%); ν_{max} (neat) / cm^{-1}; 2967, 1686, 1520, 1506, 1479; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68 (1H, app d, *J* = 2.3 Hz, Ar*H*), 7.61 (1H, app d, *J* = 1.7 Hz, Ar*H*), 7.39 (1H, d, *J* = 8.3 Hz, Ar*H*), 7.26 (1H, dd, *J* = 8.3, 1.9 Hz, Ar*H*), 7.00 (1H, d, *J* = 1.9 Hz, Ar*H*), 6.37 (1H, t, *J* = 2.3 Hz, Ar*H*), 2.66 (2H, q, *J* = 7.6 Hz, C$H_2$$CH_3$), 1.23 (3H, t, *J* = 7.6 Hz, CH_2CH_3), 0.98 (9H, s, C(CH_3)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.7 (Ar*C*=O), 143.1 (Ar*C*Et), 140.8 (Ar*C*H), 135.0 (Ar*C*N), 134.4 (Ar*C*), 129.1 (Ar*C*H), 129.0 (Ar*C*H), 126.5 (Ar*C*H), 122.2 (Ar*C*H), 107.6 (Ar*C*H), 45.2 (*C*(CH$_3$)$_3$), 28.3 (*C*$H_2$$CH_3$), 26.8 (C(*C*$H_3$)$_3$), 15.4 ($CH_2$*C*$H_3$); HRMS (ESI µTOF) m/z calcd for $C_{16}H_{20}N_2O$ $[M+Na]^+$: 279.1473, found: 279.1465.

1-(4-(1*H*-Pyrazol-1-yl)-[1,1'-biphenyl]-3-yl)-2,2-dimethylpropan-1-one (386a)



To a solution of 1-([1,1'-biphenyl]-4-yl)-1*H*-pyrazole **381b** (0.22 g, 1.0 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (33.2 mg, 11%); mpt. 156 – 163 °C; ν_{max} (neat) / cm^{-1}; 2955, 1675, 1607, 1526, 1489, 1453; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.79 (1H, app d, *J* = 2.3 Hz, Ar*H*), 7.72 – 7.66 (2H, m, Ar*H*), 7.62 – 7.57 (3H, m, Ar*H*), 7.51 – 7.36 (4H, m, Ar*H*), 6.46 (1H, t, *J* = 2.3 Hz, Ar*H*), 1.06 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.5 (Ar*C*=O), 141.3 (Ar*C*H), 139.9 (Ar*C*), 139.5 (Ar*C*), 135.7 (Ar*C*), 135.4 (Ar*C*), 129.1 (2 × Ar*C*H), 129.1 (Ar*C*H), 128.3 (Ar*C*H), 128.1 (Ar*C*H), 127.2 (2 × Ar*C*H), 126.0 (Ar*C*H), 122.4 (Ar*C*H), 108.1 (Ar*C*H), 45.5 (*C*(CH$_3$)$_3$), 27.0 (C(*C*H$_3$)$_3$); HRMS (ESI µTOF) m/z calcd for $C_{20}H_{20}N_2O$ $[M+Na]^+$: 327.1473, found: 327.1461.

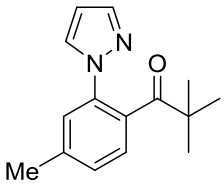
1-(5-(*tert*-Butyl)-2-(1*H*-pyrazol-1-yl)phenyl)-2,2-dimethylpropan-1-one (387a)



To a solution of 1-(4-(*tert*-butyl)phenyl)-1*H*-pyrazole **381c** (0.19 g, 0.9 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give an orange solid which was an inseparable mixture ratio of the product with the starting material (230 mg, conversion: 72% mono, 20% SM); ν_{max} (neat) / cm^{-1}; 2966, 2956, 1687,1518, 1504, 1497, 1477; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.69 (1H, app d, *J* = 2.1 Hz, Ar*H*), 7.61 (1H, app d, *J* = 0.7 Hz, Ar*H*), 7.44 (1H, d, *J* = 1.8 Hz, Ar*H*), 7.41 – 7.39 (1H, m, Ar*H*), 7.17 (1H, d, *J* = 1.8 Hz, Ar*H*), 6.36 (1H, app s, Ar*H*), 1.31 (9H, s, ArC(C*H*$_3$)$_3$), 0.99 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (125 MHz, $CDCl_3$) δ 213.8 (Ar*C*=O), 149.9 (Ar*C*^{t}Bu), 140.8 (Ar*C*H), 134.5 (Ar*C*N), 134.1 (Ar*C*), 129.0 (Ar*C*H), 126.5 (Ar*C*H), 124.1 (Ar*C*H), 121.8

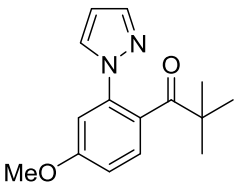
(Ar*C*H), 107.6 (Ar*C*H), 45.2 (*C*(CH_3)$_3$), 34.6 (Ar*C*(CH_3)$_3$), 31.2 (ArC(*C*H_3)$_3$), 26.8 (C(*C*H_3)$_3$); HRMS (ESI µTOF) m/z calcd for $C_{18}H_{24}N_2O$ $[M+Na]^+$: 307.1786, found: 307.1791.

2,2-Dimethyl-1-(4-methyl-2-(1*H*-pyrazol-1-yl)phenyl)propan-1-one (388a)



To a solution of 1-(*m*-tolyl)-1*H*-pyrazole **381d** (150 µL, 1.0 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as an orange oil (220 mg, 91%); ν_{max} (neat) / cm^{-1}; 2970, 1685, 1618, 1573, 1519; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.71 (1H, app d, *J* = 2.2 Hz, Ar*H*), 7.65 (1H, app d, *J* = 1.5 Hz, Ar*H*), 7.32 (1H, s, Ar*H*), 7.15 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.09 (1H, d, *J* = 7.9 Hz, Ar*H*), 6.40 (1H, t, *J* = 2.2 Hz, Ar*H*), 2.41 (3H, s, ArC*H*$_3$), 0.98 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.9 (Ar*C*=O), 141.0 (Ar*C*H) 140.0 (Ar*C*Me), 136.5 (Ar*C*N), 132.4 (Ar*C*), 129.2 (Ar*C*H), 127.6 (Ar*C*H), 127.3 (Ar*C*H), 122.9 (Ar*C*H), 107.8 (Ar*C*H), 45.4 (*C*(CH_3)$_3$), 26.8 (C(*C*H_3)$_3$), 21.3 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{15}H_{18}N_2O$ $[M+H]^+$: 243.1497, found: 243.1493.

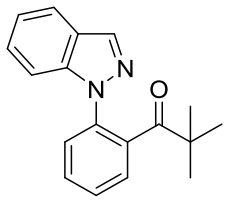
1-(4-Methoxy-2-(1*H*-pyrazol-1-yl)phenyl)-2,2-dimethylpropan-1-one (389a)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 µL, 1.0 mmol) and trimethylacetyl chloride (300 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure B and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as an orange solid (234 mg, 92%); mpt. 82 – 89 °C; ν_{max} (neat) / cm^{-1}; 2966, 1683, 1610, 1577, 1509, 1451; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.69 (1H, d, *J* = 2.3 Hz, Ar*H*), 7.62 (1H, d, *J* = 1.5 Hz, Ar*H*), 7.09 (1H, d, *J* = 8.6 Hz, Ar*H*), 6.99 (1H, d, *J* = 2.4 Hz, Ar*H*), 6.84 1H, (dd, *J* = 8.6, 2.4 Hz, Ar*H*), 6.37 (1H, t, *J* = 2.3 Hz, Ar*H*), 3.81 (3H, s, C*H*$_3$), 0.95 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.3 (Ar*C*=O), 160.3 (Ar*C*OMe), 141.1 (Ar*C*H), 137.8 (Ar*C*N), 129.2 (Ar*C*H), 128.5 (Ar*C*H), 127.5

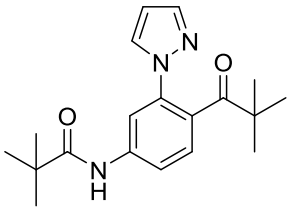
(Ar*C*), 112.4 (Ar*C*H), 107.9 (Ar*C*H), 107.7 (Ar*C*H), 55.6 (O*C*H_3), 45.4 (*C*(CH_3)$_3$), 26.8 (C(*C*H_3)$_3$); HRMS (ESI μTOF) m/z calcd for $C_{15}H_{18}N_2O_2$ $[M+Na]^+$: 281.1266, found: 281.1277.

1-(2-(1*H*-Indazol-1-yl)phenyl)-2,2-dimethylpropan-1-one (390a)



To a solution of 1-phenyl-1*H*-indazole **381e** (0.19 g, 1.0 mmol) and trimethylacetyl chloride (300 μL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as an orange solid (122 mg, 45%); mpt. 65 – 73 °C; ν_{max} (neat) / cm^{-1}; 2979, 2966, 1689, 1601, 1582, 1499, 1479, 1467, 1413; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.02 (1H, s, Ar*H*), 7.64 (1H, d, *J* = 8.1 Hz, Ar*H*), 7.54 – 7.50 (2H, m, Ar*H*), 7.40 (1H, ddd, *J* = 6.9, 2.1 Hz, Ar*H*), 7.33 – 7.22 (3H, m, Ar*H*), 7.09 (1H, t, *J* = 7.5 Hz, Ar*H*), 0.88 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.0 (Ar*C*=O), 139.4 (Ar*C*N), 137.5 (Ar*C*), 136.1 (Ar*C*), 135.5 (Ar*C*H), 129.6 (Ar*C*H), 127.8 (Ar*C*H), 127.4 (Ar*C*H), 126.9 (Ar*C*H), 125.2 (Ar*C*), 124.0 (Ar*C*H), 121.0 (Ar*C*H), 121.3 (Ar*C*H), 110.5 (Ar*C*H), 45.0 (*C*(CH_3)$_3$), 27.3 (C(*C*H_3)$_3$); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{18}N_2O$ $[M+H]^+$: 279.1497, found: 279.1518.

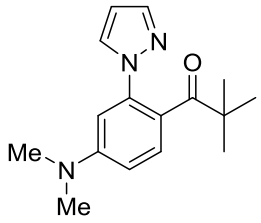
***N*-(4-Pivaloyl-3-(1*H*-pyrazol-1-yl)phenyl)pivalamide (391a)**



To a solution of *N*-(3-(1*H*-pyrazol-1-yl)phenyl)pivalamide **381f** (0.23 g, 1.0 mmol) and trimethylacetyl chloride (300 μL, 2.4 mmol) in dry toluene (3 mL) were reacted under the General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product a yellow oil (6.4 mg, 2%). ν_{max} (neat) / cm^{-1}; 2967, 1673, 1593, 1518, 1401; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.93 (1H, s, ArN*H*), 7.80 (1H, d, *J* = 2.1 Hz, Ar*H*), 7.65 (1H, d, *J* = 1.7 Hz, Ar*H*), 7.60 (1H, s, Ar*H*), 7.40 (1H, d, *J* = 8.3 Hz, Ar*H*), 7.13 (1H, d, *J* = 8.3 Hz, Ar*H*), 6.42 (1H, t, *J* = 1.7 Hz, Ar*H*), 1.33 (9H, s, C(C*H*$_3$)$_3$), 0.99 (9H, s, C(C*H*$_3$)$_3$); ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.2

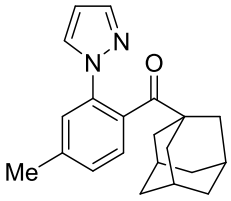
(Ar*C*=ONH), 141.1 (Ar*C*H), 139.5 (Ar*C*H), 137.0 (Ar*C*N), 130.3 (Ar*C*H), 130.1 (Ar*C*), 129.1 (Ar*C*H), 128.2 (Ar*C*H), 117.7 (Ar*C*H), 112.9 (Ar*C*H), 108.2 (Ar*C*H), 107.9 (Ar*C*), 45.4 (*C*$(CH_3)_3$), 40.0 (*C*$(CH_3)_3$), 27.7 (C(*C*$H_3)_3$), 26.9 (C(*C*$H_3)_3$); HRMS (ESI μTOF) m/z calcd for $C_{19}H_{25}N_3O_2$ $[M+Na]^+$: 350.1844, found: 350.1843.

1-(4-(Dimethylamino)-2-(1*H*-pyrazol-1-yl)phenyl)-2,2-dimethylpropan-1-one (392a)



To a solution of *N,N*-dimethyl-3-(1*H*-pyrazol-1-yl)aniline **381g** (0.19 g, 1.0 mmol) and trimethylacetyl chloride (300 μL, 2.4 mmol) in dry toluene (3 mL) were reacted under the General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product a white amorphous solid (10.0 mg, 4%); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.69 (1H, d, *J* = 2.0 Hz, Ar*H*), 7.66 (1H, s, Ar*H*), 7.09 (1H, d, *J* = 8.6 Hz, Ar*H*), 6.76 (1H, d, *J* = 2.4 Hz, Ar*H*), 6.65 (1H, dd, *J* = 8.6, 2.4 Hz, Ar*H*), 6.41 – 6.39 (1H, m, Ar*H*), 3.02 (6H, s, N(C$H_3)_2$), 0.97 (9H, s, C(C$H_3)_3$); ^{13}C NMR (125 MHz, $CDCl_3$) δ 214.2 (Ar*C*=O), 151.3 (Ar*C*NMe_2), 140.9 (Ar*C*H), 138.1 (Ar*C*N), 129.8 (Ar*C*H), 128.5 (Ar*C*H), 123.3 (Ar*C*), 110.4 (Ar*C*H), 107.4 (Ar*C*H), 106.1 (Ar*C*H), 45.9 (*C*$(CH_3)_3$), 40.4 (N(*C*$H_3)_2$), 27.1 (C(*C*$H_3)_3$); HRMS (ESI μTOF) m/z calcd for $C_{16}H_{21}N_3O$ $[M+H]^+$: 272.1763, found: 272.1759.

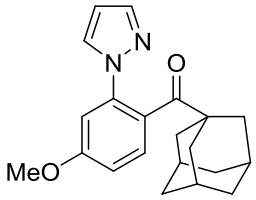
((3*r*,5*r*,7*r*)-Adamantan-1-yl)(4-methyl-2-(1*H*-pyrazol-1-yl)phenyl)methanone (393a)



To a solution of 1-(*m*-tolyl)-1*H*-pyrazole **381d** (150 μL, 1.0 mmol) and 1-adamantanecarbonyl chloride (0.49 g, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a white solid (169 mg, 54%); mpt. 105 – 116 °C; ν_{max} (neat) / cm^{-1}; 2906, 2851, 1683, 1604, 1580, 1519, 1450; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.67 (1H, d, *J* = 2.3 Hz, Ar*H*), 7.64 (1H, s,

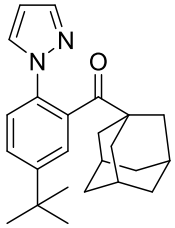
Ar*H*), 7.33 (1H, s, Ar*H*), 7.13 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.04 (1H, d, *J* = 7.8 Hz, Ar*H*), 6.38 – 6.37 (1H, m, Ar*H*), 2.39 (3H, s, ArCH_3), 1.87 (3H, br s, C*H*), 1.66 – 1.45 (12H, m, C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.1 (Ar*C*=O), 141.0 (Ar*C*H), 139.8 (Ar*C*Me), 136.5 (Ar*C*N), 132.0 (Ar*C*), 129.6 (Ar*C*H), 127.5 (Ar*C*H), 127.3 (Ar*C*H), 123.2 (Ar*C*H), 107.6 (Ar*C*H), 47.5 (*C*H$(CH_2)_3$), 38.0 (3 × *C*H), 36.4 (3 × *C*H), 27.9 (3 × *C*H), 21.2 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{21}H_{24}N_2O$ $[M+Na]^+$: 343.1786, found: 343.1804.

((3*r*,5*r*,7*r*)-Adamantan-1-yl)(4-methoxy-2-(1*H*-pyrazol-1-yl)phenyl)methanone (394a)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 μL, 1.0 mmol) and 1-adamantanecarbonyl chloride (0.49 g, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a white powder solid (173 mg, 52%); mpt. 151 – 159 °C; ν_{max} (neat) / cm^{-1}; 2907, 2849, 1674, 1609, 1577, 1510, 1447; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.66 (1H, app d, *J* = 2.3 Hz, Ar*H*), 7.63 (1H, app d, *J* = 1.6 Hz, Ar*H*), 7.05 (1H, d, *J* = 8.5 Hz, Ar*H*), 7.02 (1H, d, *J* = 2.3 Hz, Ar*H*), 6.84 (1H, dd, *J* = 8.5, 2.3 Hz, Ar*H*), 6.37 (1H, t, *J* = 1.6 Hz, Ar*H*), 3.81 (3H, s, ArCH_3), 1.85 (3H, br s, C*H*), 1.64 – 1.43 (12H, m, C*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 212.8 (Ar*C*=O), 160.3 (Ar*C*OMe), 141.1 (Ar*C*H), 137.8 (Ar*C*N), 129.6 (Ar*C*H), 128.6 (Ar*C*H), 127.1 (Ar*C*), 112.6 (Ar*C*H), 107.9 (Ar*C*H), 107.7 (Ar*C*H), 55.6 (ArO*C*H_3), 47.6 (*C*H$(CH_2)_3$), 38.0 (3 × *C*H), 36.4 (3 x *C*H), 27.9 (3 × *C*H); HRMS (ESI μTOF) m/z calcd for $C_{21}H_{24}N_2O_2$ $[M+H]^+$: 337.1916, found: 337.1922.

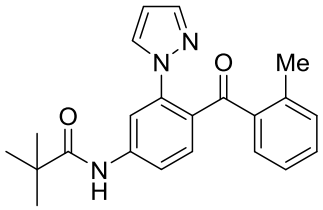
((3*r*,5*r*,7*r*)-Adamantan-1-yl)(5-(*tert*-butyl)-2-(1*H*-pyrazol-1-yl)phenyl)methanone (395a)



To a solution of 1-(4-(*tert*-butyl)phenyl)-1*H*-pyrazole **381c** (0.19 g, 1.0 mmol) and 1-adamantanecarbonyl chloride (0.49 mg, 2.5 mmol) in dry toluene (3 mL) were reacted according

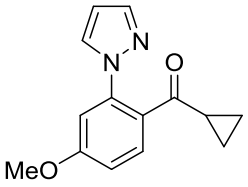
to General Procedure VI and was purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a white solid (173 mg, 52%); mpt. 152 – 156 °C; ν_{max} (neat) / cm^{-1}; 3114, 2903, 1678, 1516; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.67 – 7.65 (2H, m, Ar*H*), 7.48 (1H, dd, *J* = 8.4, 1.9 Hz, Ar*H*), 7.43 (1H, d, *J* = 8.4 Hz, Ar*H*),7.13 (1H, d, *J* = 1.9 Hz, Ar*H*), 6.39 (1H, t, *J* = 2.1 Hz, Ar*H*), 1.89 (3H, s, C*H*), 1.67 – 1.49 (12H, m, C*H*), 1.34 (9H, s, $C(CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.5 (Ar*C*=O), 150.0 (Ar*C*^{t}Bu), 140.9 (Ar*C*H), 134.4 (Ar*C*N), 134.2 (Ar*C*), 129.6 (Ar*C*H), 126.6 (Ar*C*H), 124.2 (Ar*C*H), 122.5 (Ar*C*H), 107.6 (Ar*C*H), 47.5 ($CH(CH_2)_3$), 38.1 (3 × *C*H), 36.5 (3 × *C*H), 34.8 ($C(CH_3)_3$), 31.3 ($C(CH_3)_3$), 28.0 (3 × *C*H); HRMS (ESI µTOF) m/z calcd for $C_{24}H_{30}N_2O$ $[M+Na]^+$: 385.2256, found: 385.2269.

_N_-(4-(2-Methylbenzoyl)-3-(1*H*-pyrazol-1-yl)phenyl)pivalamide (396a)



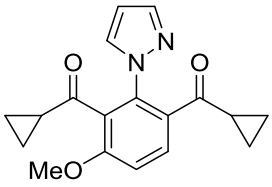
On a 0.5 mmol scale: to a solution of $[RuCl_2(p\text{-cymene})]_2$ (0.01 g, 0.02 mmol), PCy_3 (0.014 g, 0.05 mmol), K_2CO_3 (0.35 g, 0.3 mmol), *N*-(3-(1*H*-pyrazol-1-yl)phenyl)pivalamide **381f** (0.12 g, 0.5 mmol) and *o*-toluoyl chloride (160 µL, 1.2 mmol) in toluene (0.15 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (2/8) to give the desired product as a pale yellow solid (24.7 mg, 14%); mpt. 141 – 152 °C; ν_{max} (neat) / cm^{-1}; 3390, 2966, 1681, 1652, 1606, 1583, 1535, 1515, 1474; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.73 (1H, s, C(O)N*H*), 8.57 (1H, dd, *J* = 8.3, 0.9 Hz, Ar*H*), 7.57 (1H, t, *J* = 8.3 Hz, Ar*H*), 7.41 (1H, d, *J* = 2.2 Hz, Ar*H*), 7.32 (1H, d, *J* = 1.7 Hz, Ar*H*), 7.16 – 7.11 (2H, m, Ar*H*), 7.03 (1H, d, *J* = 7.4 Hz, Ar*H*), 6.88 (2H, d, *J* = 3.9 Hz, Ar*H*), 6.00 (1H, t, *J* = 1.7 Hz, Ar*H*), 2.54 (3H, s, ArCH_3), 1.27 (9H, s, $C(CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.4 (Ar*C*=O), 177.8 (*C*=ONH), 141.4 (Ar*C*H), 140.4 (Ar*C*NH), 139.3 (Ar*C*N), 139.2 (Ar*C*), 137.9 (Ar*C*), 132.4 (Ar*C*H), 131.5 (Ar*C*H), 131.4 (Ar*C*H), 129.1 (Ar*C*H), 128.7 (Ar*C*H), 124.6 (Ar*C*H), 122.9 (Ar*C*), 120.9 (Ar*C*H), 118.1 (Ar*C*H), 108.0 (Ar*C*H), 40.2 ($C(CH_3)_3$), 27.6 ($C(CH_3)_3$), 20.7 (ArCH_3); HRMS (ESI µTOF) m/z calcd for $C_{22}H_{23}N_3O_2$ $[M+H]^+$: 362.1869, found: 362.1884.

Cyclopropyl(4-methoxy-2-(1*H*-pyrazol-1-yl)phenyl)methanone (397a)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 µL, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a yellow oil (120 mg, 51%); ν_{max} (neat) / cm^{-1}; 2926, 1668, 1606, 1576, 1518, 1454; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68 (1H, app d, *J* = 1.8 Hz, Ar*H*), 7.61 (1H, app d, *J* = 2.4 Hz, Ar*H*), 7.54 (1H, d, *J* = 8.6 Hz, Ar*H*), 6.99 (1H, d, *J* = 2.4 Hz, Ar*H*), 6.91 (1H, dd, *J* = 8.6, 2.4 Hz, Ar*H*), 6.40 (1H, t, *J* = 1.8 Hz, Ar*H*), 3.82 (3H, s, OCH_3), 1.42 (1H, tt, *J* = 7.5, 4.0 Hz, C*H*), 0.99 (2H, dt, *J* = 7.5, 4.0, CH_2), 0.66 (2H, dt, *J* = 7.5, 4.0 Hz, CH_2); ^{13}C NMR (75 MHz, $CDCl_3$) δ 202.6 (Ar*C*=O), 162.1 (Ar*C*OMe), 141.5 (Ar*C*H), 140.5 (Ar*C*N), 131.2 (Ar*C*H), 130.7 (Ar*C*H), 128.7 (Ar*C*), 113.9 (Ar*C*H), 110.3 (Ar*C*H), 107.6 (Ar*C*H), 55.7 (O*C*H_3), 20.5 (*C*H), 12.6 (2 × *C*H_2); HRMS (ESI µTOF) m/z calcd for $C_{14}H_{14}N_2O_2$ $[M+Na]^+$: 265.0953, found: 265.0964.

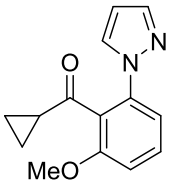
(4-Methoxy-2-(1*H*-pyrazol-1-yl)-1,3-phenylene)bis(cyclopropylmethanone) (397b)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 µL, 1.0 mmol) and cyclopropanecarbonyl chloride (220 µL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and was purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give a yellow oil which was an inseparable mixture ratio of the product and the dimer 1,1'-(4,4'-dimethoxy-[1,1'-biphenyl]-2,2'-diyl)bis(1H-pyrazole) (48.8 mg, conversion: **397b** = 13%, dimer = 2%); ν_{max} (neat) / cm^{-1}; 2927, 1688, 1665, 1592, 1517, 1482; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68 (1H, d, *J* = 8.7 Hz, Ar*H*), 7.65 (1H, d, *J* = 1.6 Hz, Ar*H*), 7.57 (1H, d, *J* = 2.2 Hz, Ar*H*), 7.05 (1H, d, *J* = 8.7 Hz, Ar*H*), 6.40 (1H, t, *J* = 2.2 Hz, Ar*H*), 3.91 (3H, s, OC*H*3), 1.96 (1H, tt, *J* = 7.6, 4.3 Hz, C*H*), 1.39 (1H, tt, *J* = 7.8, 4.1 Hz, C*H*), 1.05 – 0.96 (4H, m, 2 x CH_2), 0.82 (2H, dt, *J* = 7.6,

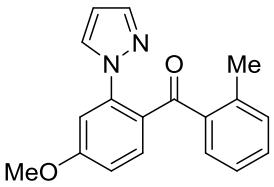
4.3 Hz, CH_2), 0.64 (2H, dt, *J* = 7.8, 4.1 Hz, 2 × CH_2); ^{13}C NMR (75 MHz, $CDCl_3$) δ 203.4 (Ar*C*=O), 202.0 (Ar*C*=O), 158.4 (Ar*C*OMe), 141.4 (Ar*C*H), 136.8 (Ar*C*N), 133.0 (Ar*C*H), 131.3 (Ar*C*H), 130.8 (Ar*C*), 129.0 (Ar*C*), 111.1 (Ar*C*H), 107.7 (Ar*C*H), 56.5 (O*C*H3), 23.2 (*C*H), 19.9 (*C*H), 12.7 (2 × *C*H_2), 12.4 (2 × *C*H_2); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{18}N_2O_3$ $[M+Na]^+$: 333.1215, found: 333.1220.

Cyclopropyl(2-methoxy-6-(1*H*-pyrazol-1-yl)phenyl)methanone (397c)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 μL, 1.0 mmol) and cyclopropanecarbonyl chloride (220 μL, 2.4 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a yellow oil (12.7 mg, 5%). ν_{max} (neat) / cm^{-1}; 2940, 1684, 1598, 1583, 1518, 1469; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.67 – 7.66 (2H, m, Ar*H*), 7.42 (1H, t, *J* = 8.3 Hz, Ar*H*), 7.13 (1H, d, *J* = 8.3 Hz, Ar*H*), 6.95 (1H, d, *J* = 8.3 Hz, Ar*H*), 6.39 (1H, t, *J* = 2.1 Hz, Ar*H*), 3.87 (3H, s, OCH_3), 2.01 (1H, tt, *J* = 7.8, 4.1 Hz, C*H*), 1.08 (2H, dt, *J* = 7.8, 4.1 Hz, CH_2), 0.85 (2H, dt, *J* = 7.8, 4.1 Hz, CH_2); ^{13}C NMR (125 MHz, $CDCl_3$) δ 204.3 (Ar*C*=O), 156.9 (Ar*C*OMe), 141.1 (Ar*C*H), 138.4 (Ar*C*N), 130.7 (Ar*C*H), 130.5 (Ar*C*H), 126.5 (Ar*C*), 116.7 (Ar*C*H), 110.5 (Ar*C*H), 107.4 (Ar*C*H), 56.4 (OCH_3), 23.7 (*C*H), 12.1 (2 × *C*H_2); HRMS (ESI μTOF) m/z calcd for $C_{14}H_{14}N_2O_2$ $[M+Na]^+$: 265.0953, found: 265.0938.

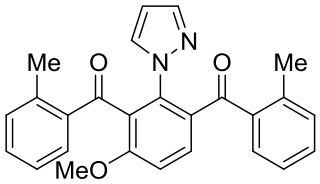
(4-Methoxy-2-(1*H*-pyrazol-1-yl)phenyl)(*o*-tolyl)methanone (398a)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 μL, 1.0 mmol) and *o*-toluoyl chloride (320 μL, 2.5 mmol) in dry toluene (3 mL) were reacted under the General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a yellow oil (23.5 mg, 8%); ν_{max} (neat) / cm^{-1}; 2927, 1669, 1596, 1571, 1521, 1467; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.65 – 7.59 (1H, m, Ar*H*), 7.49 (1H, d, *J* = 2.3 Hz, Ar*H*), 7.39 (1H, d, *J* = 1.6

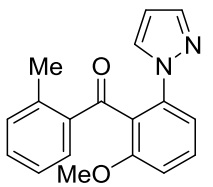
Hz, Ar*H*), 7.19 (1H, td, *J* = 7.5, 1.1 Hz, Ar*H*), 7.12 – 7.05 (2H, m, Ar*H*), 7.01 (1H, s, Ar*H*), 6.99 – 6.93 (2H, m, Ar*H*), 6.11 (1H, t, *J* = 2.3 Hz, Ar*H*), 3.91 (3H, s, OCH_3), 2.53 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.8 (Ar*C*=O), 162.3 (Ar*C*OMe), 141.2 (Ar*C*H), 141.0 (Ar*C*N), 139.0 (Ar*C*), 137.6 (Ar*C*), 132.5 (Ar*C*H), 131.4 (Ar*C*H), 131.1 (Ar*C*H), 129.8 (Ar*C*H), 129.7 (Ar*C*H), 128.0 (Ar*C*), 124.8 (Ar*C*H), 113.5 (Ar*C*H), 109.7 (Ar*C*H), 107.5 (Ar*C*H), 55.9 (O*C*H_3), 20.9 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{16}N_2O_2$ $[M+H]^+$: 293.1290, found: 293.1311.

(4-Methoxy-2-(1H-pyrazol-1-yl)-1,3-phenylene)bis(o-tolylmethanone) (398b)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 μL, 1.0 mmol) and *o*-toluoyl chloride (320 μL, 2.5 mmol) in dry toluene (3 mL) were reacted under the General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a beige solid (14.9 mg, 4%); mpt. 126 – 135 °C; ν_{max} (neat) / cm^{-1}; 2928, 1663, 1590, 1479, 1458; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.82 (1H, d, *J* = 8.6 Hz, Ar*H*), 7.29 – 7.20 (3H, m, Ar*H*), 7.18 – 6.99 (7H, m, Ar*H*), 6.94 (1H, t, *J* = 7.4 Hz, Ar*H*), 5.73 (1H, t, *J* = 2.0 Hz, Ar*H*), 3.89 (3H, s, OCH_3), 2.52 (3H, s, ArCH_3), 2.45 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 196.3 (Ar*C*=O), 195.3 (Ar*C*=O), 159.3 (Ar*C*OMe), 141.1 (Ar*C*H), 140.2 (Ar*C*N), 138.8 (Ar*C*), 137.6 (Ar*C*), 137.1 (Ar*C*), 135.5 (Ar*C*), 132.9 (Ar*C*H), 132.6 (Ar*C*H), 131.9 (Ar*C*H), 131.8 (Ar*C*H), 131.3 (Ar*C*H), 131.1 (Ar*C*H), 130.2 (Ar*C*), 129.7 (Ar*C*H), 127.3 (Ar*C*), 125.6 (Ar*C*H), 124.7 (Ar*C*H), 110.8 (Ar*C*H), 107.1 (Ar*C*H), 56.6 (O*C*H_3), 21.7 (Ar*C*H_3), 20.7 (Ar*C*H_3); HRMS (ESI μTOF) m/z calcd for $C_{26}H_{22}N_2O_3$ $[M+Na]^+$: 433.1528, found: 433.1546.

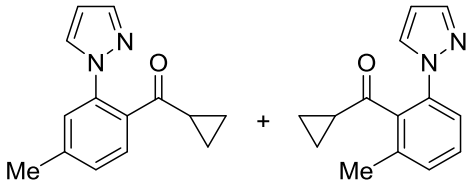
(2-Methoxy-6-(1*H*-pyrazol-1-yl)phenyl)(*o*-tolyl)methanone (398c)



To a solution of 1-(3-methoxyphenyl)-1*H*-pyrazole **334b** (150 μL, 1.0 mmol) and *o*-toluoyl chloride (320 μL, 2.5 mmol) in dry toluene (3 mL) were reacted under the General Procedure VI and

purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a yellow oil (6.5 mg, 2%); mpt. 125 – 134 °C; ν_{max} ($CHCl_3$) / cm^{-1}; 1675, 1599, 1469; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.62 (1H, app d, *J* = 2.2 Hz, Ar*H*), 7.48 (1H, t, *J* = 8.1 Hz, Ar*H*), 7.44 (1H, app d, *J* = 1.4 Hz, Ar*H*), 7.33 (1H, d, *J* = 8.1 Hz, Ar*H*), 7.30 – 7.26 (1H, m, Ar*H*), 7.17 (2H, t, *J* = 7.4 Hz, Ar*H*), 7.05 (1H, t, *J* = 7.4 Hz, Ar*H*), 6.98 (1H, d, *J* = 8.1 Hz, Ar*H*), 6.21 (1H, t, *J* = 2.2 Hz, Ar*H*), 3.78 (3H, s, OCH_3), 2.63 (3H, s, ArCH_3);^{13}C NMR (125 MHz, $CDCl_3$) δ 195.9 (Ar*C*=O), 157.9 (Ar*C*OMe), 140.9 (Ar*C*H), 140.2 (Ar*C*N), 138.8 (Ar*C)*, 136.9 (ArC), 131.9 (Ar*C*H), 131.8 (Ar*C*H), 131.5 (Ar*C*H), 130.8 (Ar*C*H), 129.9 (Ar*C*H), 125.4 (Ar*C*H), 115.9 (Ar*C*H), 110.4 (Ar*C*H), 107.3 (Ar*C*H), 56.4 (OCH_3), 21.7 (ArCH_3); HRMS (ESI μTOF) m/z calcd for $C_{18}H_{16}N_2O_2$ $[M+Na]^+$: 315.1109, found: 315.1123.

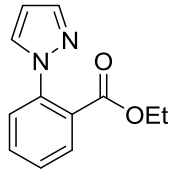
Cyclopropyl(4-methyl-2-(1*H*-pyrazol-1-yl)phenyl)methanone (399a and 399c)



399a **399c**

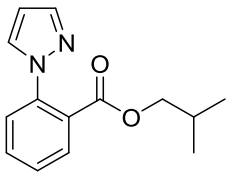
To a solution of 1-(*m*-tolyl)-1*H*-pyrazole **381d** (150 μL, 1.0 mmol) and cyclopropanecarbonyl chloride (220 μL, 2.4 mmol) in dry toluene were reacted under the General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give the desired product as a yellow oil which was an inseparable mixture ratio of the product with another mono-acylated product (78.4 mg, overall conversion 28%), ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.72 (1H, d, *J* = 1.7 Hz, Ar*H*), 7.65 (1H, d, *J* = 2.3 Hz, Ar*H*), 7.50 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.35 (1H, s, Ar*H*), 7.27 – 7.24 (1H, m, Ar*H*), 6.45 (1H, t, *J* = 2.3 Hz, Ar*H*), 2.44 (3H, s, ArCH_3), 1.55 (1H, tt, *J* = 7.8, 4.6 Hz, C*H*), 1.11 – 1.03 (2H, m, CH_2), 0.81 – 0.70 (2H, m, CH_2).^{13}C NMR (75 MHz, $CDCl_3$) δ 203.8 (Ar*C*=O), 142.6 (Ar*C*Me), 141.3 (Ar*C*N), 133.7 (Ar*C*), 131.1 (Ar*C*H), 129.0 (Ar*C*H), 128.9 (Ar*C*H), 125.9 (Ar*C*H), 107.6 (Ar*C*H), 21.4 (ArCH_3), 20.8 (*C*H), 12.8 (2 × *C*H_2); HRMS (ESI μTOF) m/z calcd for $C_{14}H_{14}N_2O$ $[M+Na]^+$: 249.1004, found: 249.1023.

Ethyl 2-(1*H*-pyrazol-1-yl)benzoate (404a)



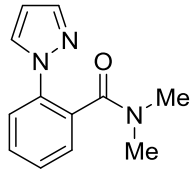
To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and ethyl chloroformate (230 µL, 2.4 mmol) in dry toleuene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give a yellow oil as product (20.1 mg, 9%); ν_{max} (neat) / cm^{-1}; 2982, 2929, 1719, 1606, 1520, 1456; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.82 (1H, dd, *J* = 7.8, 1.3 Hz, Ar*H*), 7.70 (1H, d, *J* = 1.3 Hz, Ar*H*), 7.69 (1H, d, *J* = 2.2 Hz, Ar*H*), 7.57 (1H, td, *J* = 7.8, 1.3 Hz, Ar*H*), 7.49 – 7.46 (1H, m, Ar*H*), 7.44 (1H, td, *J* = 7.7, 1.1 Hz, Ar*H*), 6.44 (1H, t, *J* = 2.2 Hz, Ar*H*), 4.18 (2H, q, *J* = 7.1 Hz, CH_2), 1.14 (3H, t, *J* = 7.1 Hz, CH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 167.0 (Ar*C*=O), 141.0 (Ar*C*H), 139.5 (Ar*C*N), 132.0 (Ar*C*H), 130.6 (Ar*C*H), 130.1 (Ar*C*H), 128.3 (Ar*C*), 128.0 (Ar*C*H), 125.6 (Ar*C*H), 107.1 (Ar*C*H), 61.5 (O*C*H_2), 14.1 (*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{12}H_{12}N_2O_2$ $[M+H]^+$: 217.0977, found: 217.0990.

***iso*Butyl 2-(1*H*-pyrazol-1-yl)benzoate (404b)**



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and isobutyl chloroformate (320 µL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to give a yellow oil as product (16.0 mg, 7%); ν_{max} (neat) / cm^{-1}; 2961, 2875, 1722, 1606, 1585, 1521, 1456; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.82 (1H, dd, *J* = 7.8, 1.4 Hz, Ar*H*), 7.69 (2H, d, *J* = 2.1 Hz, Ar*H*), 7.57 (1H, td, *J* = 7.8, 1.4 Hz, Ar*H*), 7.47 (1H, d, *J* = 7.9 Hz, Ar*H*), 7.46 – 7.42 (1H, m, Ar*H*), 6.44 (1H, t, *J* = 2.1 Hz, Ar*H*), 3.92 (2H, d, *J* = 6.7 Hz, CH_2), 1.80 (1H, dp, *J* = 13.5, 6.7 Hz, C*H*), 0.82 (6H, d, *J* = 6.7 Hz, 2 × CH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 167.1 (Ar*C*=O), 141.1 (Ar*C*H), 139.5 (Ar*C*N), 132.0 (Ar*C*H), 130.6 (Ar*C*H), 130.0 (Ar*C*H), 128.1 (Ar*C*), 127.9 (Ar*C*H), 125.6 (Ar*C*H), 107.2 (Ar*C*H), 71.8 (O*C*H_2), 27.6 (*C*H), 19.2 (2 × *C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{14}H_{16}N_2O_2$ $[M+H]^+$: 245.1290, found: 245.1278.

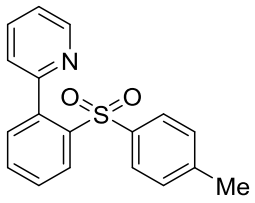
***N,N*-Dimethyl-2-(1*H*-pyrazol-1-yl)benzamide (404c)**



To a solution of 1-phenylpyrazole (130 µL, 1.0 mmol) and dimethylcarbamyl chloride (230 µL, 2.5 mmol) in dry toluene (3 mL) were reacted according to General Procedure VI and purified by flash column chromatography eluting with (EtOAc/hexane) (3/7) to afford the product as a dark brown oil (20.7 mg, 10%); ν_{max} (neat) / cm^{-1}; 3114, 2930, 2015, 1945, 1727, 1624, 1605, 1581, 1519, 1484, 1452; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.79 (1H, dd, *J* = 2.5, 0.5 Hz, Ar*H*), 7.70 (1H, dd, *J* = 1.8, 0.5 Hz, Ar*H*), 7.63 – 7.61 (1H, m, Ar*H*), 7.53 – 7.49 (1H, m, Ar*H*), 7.42 – 7.41 (2H, m, Ar*H*), 6.43 (dd, *J* = 2.5, 0.5 Hz, Ar*H*), 2.97 (3H, s, CH_3), 2.53 (3H, s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.4 (Ar*C*=O), 141.4 (Ar*C*H), 137.1 (Ar*C*N), 130.8 (Ar*C*), 130.2 (Ar*C*H), 129.8 (Ar*C*H), 128.2 (Ar*C*H), 127.9 (Ar*C*H), 124.0 (Ar*C*H), 107.5 (Ar*C*H), 38.2 (*C*H_3), 34.8 (*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{12}H_{13}N_3O$ $[M+H]^+$: 216.1137, found: 216.1135.

5.4. Chapter 4 Experimental Procedures

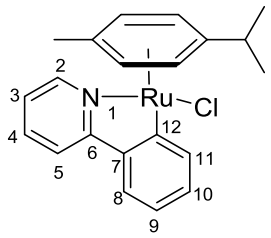
2-(2-Tosylphenyl)pyridine (315a)[30]



To an oven dried carousel tube was added 4 Å molecular sieves (0.53 g), [Pd($CH_3CN)_2$] (27 mg, 0.1 mmol), K_2CO_3 (0.27 g, 2.0 mmol), *p*-toluenesulfonyl chloride (0.56 g, 2.9 mmol), 2-phenylpyridine (140 µL, 1.0 mmol) and anhydrous 1,4-dioxane (3 mL) and sealed under an atmosphere of N_2 and then heated at 120 °C with stirring. After 24 h, the reaction mixture was filtered through a pad of Celite® and washed with EtOAc (250 mL), the filtrate was concentrated *in vacuo*. The brown residue was purified by flash column chromatography eluting with (EtOAc/ hexane) (1/9) to afford the title compound as a brown crystalline solid (115 mg, 38%), mpt. 107 – 120 °C, (Lit.[30] 107 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.37 (1H, ddd, *J* = 4.9, 1.6, 0.9 Hz, Ar*H*), 8.33 – 8.28 (1H, m, Ar*H*), 7.70 (1H, td, *J* = 7.7, 1.8 Hz, Ar*H*), 7.64 – 7.53 (2H, m, Ar*H*), 7.50 (1H, d, *J* = 7.8 Hz, Ar*H*), 7.36 – 7.28 (3H, m, Ar*H*), 7.24 (1H, ddd, *J* = 7.5, 4.9, 1.1 Hz, Ar*H*), 7.08 (2H, d, *J* = 8.1 Hz, Ar*H*), 2.32 (3H, s, ArCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.7 (Ar*C*N), 148.4 (Ar*C*HN), 143.7 (Ar*C*), 140.7 (Ar*C*), 139.7 (Ar*C*),

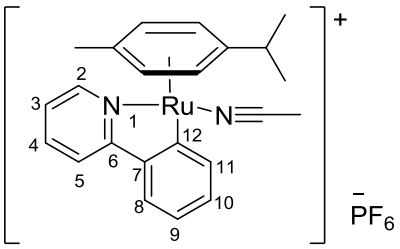
138.4 (Ar*C*), 135.6 (Ar*C*H), 133.0 (Ar*C*H), 132.1 (Ar*C*H), 129.3 (2 × Ar*C*H), 129.0 (Ar*C*H), 128.7 (Ar*C*H), 127.8 (2 × Ar*C*H), 125.9 (Ar*C*H), 122.6 (Ar*C*H), 21.5 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{18}H_{15}NO_2S$ $[M+Na]^+$: 332.0721, found: 332.0707.

[2-Phenylpyridine ruthenium (*p*-cymene) chloride] (319)[31]



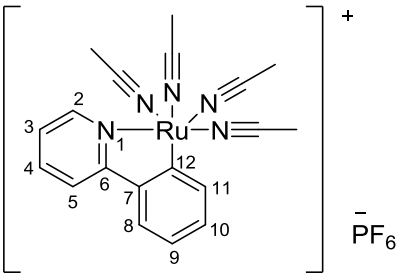
[Ru(*p*-cymene)Cl_2]$_2$ (0.31 g, 0.5 mmol), KOAc (0.20 g, 2.0 mmol), dry MeOH (10 mL) and 2-phenylpyrdine (140 µL, 1.0 mmol) were introduced to a flame-dried flask equipped with a magnetic stirring bar under Ar. The mixture was stirred at room temperature for 39 h. The solvent was removed under reduced pressure and then dissolved with a minimum amount of EtOAc and the crude reaction mixture was purified through oven-dried neutral alumina (Al_2O_3) and eluted with EtOAc. The yellow/orange fraction was collected and the solvent was removed under vacuum to give the desired product as a flakey orange solid (372 mg, 89%); mpt. (dec.) 200 – 205 °C; ν_{max} (neat) / cm^{-1}; 3039, 2960, 2920, 2863, 1601, 1578, 1561, 1547, 1507, 1479, 1455, 1435, 1411; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.23 (1H, d, *J* = 5.7 Hz, ArH_2), 8.15 (1H, d, *J* = 7.5 Hz, ArH_8), 7.73 – 7.60 (3H, m, ArH_4, ArH_5 & ArH_{10}), 7.18 (1H, td, *J* = 7.5, 1.0 Hz, ArH_9), 7.08 – 7.00 (2H, m, ArH_3 & ArH_{11}), 5.57 (2H, d, *J* = 6.1 Hz, cymene Ar*H*), 5.17 (1H, d, *J* = 6.1 Hz, cymene Ar*H*), 4.98 (1H, d, *J* = 6.1 Hz, cymene Ar*H*), 2.43 (1H, hept, *J* = 6.9 Hz, C*H*Me_2), 2.04 (3H, s, ArCH_3), 0.98 (3H, d, *J* = 6.9 Hz, CHMeCH_3), 0.88 (3H, d, *J* = 6.9 Hz, CHMeCH_3); ^{13}C NMR (125 MHz, $CDCl_3$) δ 183.5 (Ar*C*Ru), 165.5 (Ar*C*N), 154.7 (Ar*C*HN), 143.5 (Ar*C*), 139.7 (Ar*C*H), 136.7 (Ar*C*H), 129.6 (Ar*C*H), 124.0 (Ar*C*H), 122.7 (Ar*C*H), 121.5 (Ar*C*H), 118.9 (Ar*C*H), 100.8 (Ar*C*), 100.7 (Ar*C*), 90.9 (Ar*C*H), 89.8 (Ar*C*H), 84.3 (Ar*C*H), 82.3 (Ar*C*H), 30.9 (*C*HMe_2), 22.7 (CHMe*C*H_3), 21.9 (CHMe*C*H_3), 18.9 (Ar*C*H_3); HRMS (ESI µTOF) m/z calcd for $C_{21}H_{22}NRuCl$ $[M+Na]^+$: 448.0379, found: 448.0378.

[2-Phenylpyridine ruthenium (*p*-cymene) acetonitrile] hexaflurophosphate complex (410)[31]



To a flame-dried flask equipped with a magnetic stirring bar and under Ar was added complex **319** (110 mg, 0.3 mmol) and $AgPF_6$ (90 mg, 0.4 mmol) in dry MeCN (2.5 mL). The flask was sealed in an atmosphere of Ar and stirred at room temperature for 1 h. The reaction mixture was filtered through oven-dried neutral alumina (Al_2O_3) and eluted with MeCN and collecting the yellow band. The solvent was removed *in vacuo* to afford complex **410** as a yellow solid (143 mg, 98%); mpt. (dec.) 196 – 201 °C; ν_{max} (neat) / cm^{-1}; 2967, 2936, 2875, 1606, 1580, 1565, 1538, 1510, 1480, 1438, 1417; ^{1}H NMR (300 MHz, CD_3CN) δ 9.17 (1H, dd, *J* = 5.7, 0.6 Hz, ArH_2), 8.11 (1H, d, *J* = 7.5 Hz, ArH_8), 7.91 – 789 (2H, m, ArH_4 & ArH_5), 7.74 (1H, d, *J* = 7.5 Hz, ArH_{11}), 7.28 – 7.17 (2H, m, ArH_3 & ArH_9), 7.12 (1H, t, *J* = 7.5 Hz, ArH_{10}), 5.91 (2H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.62 (2H, d, *J* = 6.2 Hz, cymene Ar*H*), 2.33 (1H, hept, *J* = 7.0 Hz, C*H*Me2), 1.97 (3H, s, NCCH_3), 1.94 (3H, s, ArCH_3), 0.91 (3H, d, *J* = 7.0 Hz, CHMeCH_3), 0.87 (3H, d, *J* = 7.0 Hz, CHMeCH_3); ^{13}C NMR (125 MHz, CD_3CN) δ 166.5 (Ar*C*Ru), 156.6 (Ar*C*), 145.3 (Ar*C*), 141.0 (Ar*C*H), 139.6 (Ar*C*H), 130.6 (Ar*C*H), 125.2 (Ar*C*H), 124.7 (Ar*C*H), 123.6 (Ar*C*H), 120.4 (Ar*C*H), 104.9 (cymene Ar*C*), 103.2 (cymene Ar*C*), 93.3 (2 × Ar*C*H), 89.1 (Ar*C*H), 85.6 (Ar*C*H), 31.8 (*C*HMe$_2$), 22.4 (CHMe*C*H$_3$), 22.1 (CHMe*C*H$_3$), 18.8 (Ar*C*H$_3$); ^{31}P NMR (162 MHz, CD_3CN) δ -144.50 (app quint, *J* = 706.1 Hz); ^{19}F NMR (376 MHz, CD_3CN) δ -72.92 (d, *J* = 706.4 Hz); HRMS (ESI µTOF) m/z calcd for $C_{21}H_{22}NRu$ (2phpyRu(*p*-cymene))$^+$ $[M]^+$: 390.0796, found: 390.0864.

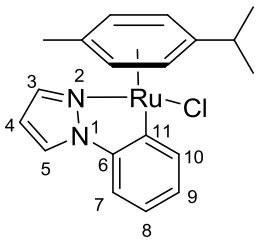
[2-Phenylpyridne ruthenium tetra acetonitrile] hexaflurophosphate complex (411)[31]



To a flame-dried carousel tube equipped with a magnetic stirrer bar under Ar and was added complex **410** (80 mg, 0.2 mmol) and dry MeCN (2 mL). The flask was sealed under an atmosphere

of Ar and the mixture was heated at 85 °C with stirring for 6.5 days. The reaction mixture was filtered through oven-dried neutral alumina (Al_2O_3) and eluted with dry MeCN and collecting the yellow band. The solvent was removed *in vacuo* and triturated with dry Et_2O (8 mL). Et_2O was removed by cannula filtration, and the precipitate was washed with Et_2O (2 × 5 mL) and removed the solvent *via* cannula filtration. The lime green solid was dried under high vacuum and stored under Ar (65.2 mg, 60%); mpt. (dec.) 170 – 175 °C; ν_{max} (neat) / cm^{-1}; 2969, 2937, 2322, 2269, 1650, 1606, 1577, 1474, 1414; ^{1}H NMR (300 MHz, CD_3CN) δ 8.91 (1H, d, *J* = 6.1 Hz, ArH_2), 7.96 (1H, d, *J* = 7.3 Hz, ArH_8), 7.88 (1H, d, *J* = 8.0 Hz, ArH_5), 7.78 – 7.68 (2H, m, ArH_4 & ArH_{11}), 7.15 (1H, t, *J* = 6.1 Hz, ArH_3), 7.08 (1H, t, *J* = 7.3 Hz, ArH_9), 6.95 (1H, t, *J* = 7.3 Hz, ArH_{10}), 2.01 (6H, s, 2 × CH_3CN); ^{13}C NMR (125 MHz, CD_3CN) δ 184.9 (Ar*C*Ru), 169.1 (Ar*C*), 153.3 (Ar*C*H), 147.8 (Ar*C*), 139.2 (Ar*C*H), 137.0 (Ar*C*H), 128.4 (Ar*C*H), 124.0 (Ar*C*H), 123.9 (*C*N), 122.1 (Ar*C*H), 121.9 (*C*N), 118.7 (Ar*C*H); ^{31}P NMR (162 MHz, CD_3CN) δ -144.50 (app quint, *J* = 706.4 Hz); ^{19}F NMR (376 MHz, CD_3CN) δ -72.86 (d, *J* = 706.3 Hz); HRMS (ESI μTOF) m/z calcd for $C_{17}H_{17}N_4Ru$ (2-phpyRu(MeCN))$^+$ $[M]^+$: 379.0496, found: 397.0506.

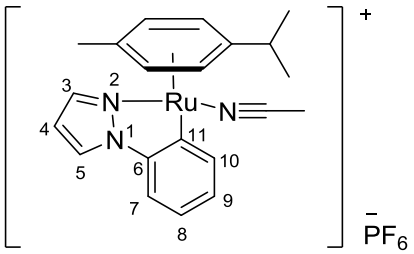
[1-Phenylpyrazole ruthenium (*p*-cymene) chloride] (333)[32]



To a flame-dried flask equipped with a magnetic stirrer bar was added $[RuCl_2(p\text{-cymene})]_2$ (0.51 g, 0.8 mmol) and KOAc (0.33 g, 3.4 mmol) in dry MeOH (16 mL) and then added 1-phenylpyrazole (0.22 mL, 1.7 mmol). The reaction mixture was sealed under an atmosphere of Ar and was allowed to stir at rt for 6 days. The solvent was removed *in vacuo* and the residue was filtered through a column of oven-dried neutral alumina (Al_2O_3) and eluted with EtOAc (100%) to afford the desired product as an orange powder (568 mg, 82%); mpt. (dec.) 201 – 208 °C; ν_{max} (neat) / cm^{-1}; 3142, 3076, 3039, 2960, 2924, 2871, 2853, 1604, 1583, 1535, 1498, 1474, 1439, 1427, 1406; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.13 (1H, dd, *J* = 7.3, 1.2 Hz, ArH_{10}), 8.05 (1H, d, *J* = 1.9 Hz, ArH_3), 7.89 (1H, d, *J* = 2.4 Hz, ArH_5), 7.18 – 7.00 (3H, m, ArH_7, ArH_8 & ArH_9), 6.46 (1H, app t, *J* = 2.4 Hz, ArH_4), 5.55 (2H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.28 (1H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.08 (1H, d, *J* = 6.2 Hz, cymene Ar*H*), 2.43 (1H, hept, *J* = 6.9 Hz, C*H*Me$_2$), 2.04 (3H, s, ArCH_3), 0.95 (3H, d, *J* = 6.9 Hz, CHMeCH_3), 0.92 (3H, d, *J* = 6.9 Hz, CHMeCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.9 (Ar*C*Ru), 142.2 (Ar*C*H), 141.9 (Ar*C*N), 140.2 (Ar*C*H), 126.1 (Ar*C*H), 125.0 (Ar*C*H), 123.2 (Ar*C*H), 111.5 (Ar*C*H), 108.4

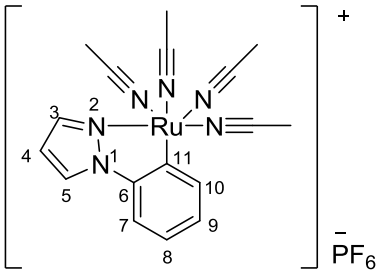
(Ar*C*H), 100.1 (2 × Ar*C*), 88.7 (Ar*C*H), 88.2 (Ar*C*H), 84.1 (Ar*C*H), 82.3 (Ar*C*H), 30.8 (Ar*C*HMe$_2$), 22.5 (ArCHMe*C*H$_3$), 22.0 (ArCHMe*C*H$_3$), 18.9 (Ar*C*H$_3$); HRMS (ESI µTOF) m/z calcd for $C_{19}H_{21}ClN_2Ru$ $[M+Na]^+$: 437.0331, found: 437.0347.

[1-Phenylpyrazole ruthenium (*p*-cymene) acetonitrile] hexafluorophosphate (412)[33]



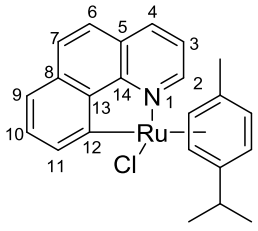
To an oven-dried Schlenk tube was added complex **333** (100 mg, 0.2 mmol), $AgPF_6$ (90 mg, 0.3 mmol) then dry MeCN (2.5 mL) and the flask was purged under Ar. The reaction mixture was allowed to stir at rt for 1 h. The resulting yellow mixture was filtered through a column of oven-dried neutral alumina (Al_2O_3) and eluted with MeCN. The yellow band was collected and concentrated *in vacuo* to afford the product as a yellow powder (128 mg, 97%); mpt. (dec.) 199 – 207 °C; ν_{max} (neat) / cm^{-1}; 3162, 2974, 2940, 1510, 1479, 1405; ^{1}H NMR (300 MHz, CD_3CN) δ 8.25 (1H, dd, *J* = 2.5, 0.3 Hz, Ar*H*$_3$), 8.18 (1H, d, *J* = 2.5 Hz, Ar*H*$_5$), 8.13 – 8.08 (1H, m, Ar*H*$_{10}$), 7.42 – 7.36 (1H, m, Ar*H*$_7$), 7.18 – 7.09 (2H, m, Ar*H*$_8$ & Ar*H*$_9$), 6.61 (1H, dd, *J* = 2.5, 0.3 Hz, Ar*H*$_4$), 5.89 (2H, dd, *J* = 6.2, 0.9 Hz, cymene Ar*H*), 5.71 (1H, dd, *J* = 6.2, 0.9 Hz, cymene Ar*H*), 5.46 (1H, dd, *J* = 6.2, 0.9 Hz, cymene Ar*H*), 2.32 (1H, hept, *J* = 6.5 Hz, C*H*Me$_2$), 1.96 (3H, s, ArC*H*$_3$), 1.94 (3H, s, NCC*H*$_3$), 0.90 (3H, d, *J* = 6.5 Hz, CHMeC*H*$_3$), 0.87 (3H, d, *J* = 6.5 Hz, CHMeC*H*$_3$); ^{13}C NMR (75 MHz, CD_3CN) δ 156.8 (Ar*C*Ru), 145.2 (Ar*C*HN), 143.3 (Ar*C*N), 141.5 (Ar*C*H), 128.0 (Ar*C*H), 127.0 (Ar*C*H), 125.3 (Ar*C*H), 113.0 (Ar*C*H), 109.9 (Ar*C*H), 104.5 (Ar*C*), 103.0 (Ar*C*H), 91.7 (Ar*C*H), 91.4 (Ar*C*H), 88.5 (Ar*C*H), 85.2 (Ar*C*H), 31.6 (Ar*C*HMe$_2$), 22.2 (CHMe*C*H$_3$), 22.2 (CHMe*C*H$_3$), 18.8 (Ar*C*H$_3$); ^{31}P NMR (162 MHz, CD_3CN) δ -144.51 (app quint, *J* = 706.3 Hz); ^{19}F NMR (376 MHz, CD_3CN) δ -72.92 (d, *J* = 705.9 Hz); anal. cald. for $C_{22}H_{27}F_6N_3PRu$: C 44.68, H 4.29, N 7.44; found C 44.84, H 4.15, N 7.64; HRMS (ESI µTOF) m/z calcd for $C_{19}H_{21}N_2Ru$ (phenylpyrazoleRu(*p*-cymene))$^+$ $[M]^+$: 379.0748, found: 379.0790.

[1-Phenylpyrazole ruthenium tetra acetonitrile] hexafluorophosphate (413)[33]



To an oven-dried carousel tube was added complex **333** (0.43 g, 1.0 mmol), KPF_6 (0.39 g, 2.1 mmol) in dry MeCN (8 mL), the reaction mixture was heated at 84 °C under Ar with stirring for 4 days. The reaction mixture was plugged through oven-dried neutral alumina (Al_2O_3) and eluted with dry MeCN, collecting the light yellow band. The solvent was removed under reduced pressure and dissolved the oil in minimum amount of MeCN and the precipitate was crushed out with addition of Et_2O (10 mL), and the solvent was removed via cannula filtration. The precipitate was washed with Et_2O (3 x 10 mL) and the solvent was removed *via* cannula filtration. Then the precipitate was dried under high vacuum to afford the desired complex as a turquoise green powder (517 mg, 90%); mpt. (dec.) 193 – 200 °C; ν_{max} (neat) / cm^{-1}; 3162, 2974, 2274, 1510, 1478, 1405; ^{1}H NMR (300 MHz, CD_3CN) δ 8.30 (1H, dd, *J* = 2.8, 1.3 Hz, ArH_5), 7.90 – 7.87 (2H, m, ArH_3 & ArH_{10}), 7.38 – 7.34 (1H, m, ArH_7), 7.05 – 6.95 (2H, m, ArH_8 & H_9), 6.56 (1H, dd, *J* = 2.8, 1.3 Hz, ArH_4), 2.51 (3H, s, CH_3CN), 2.22 (6H, s, 2 × CH_3CN); ^{13}C NMR (75 MHz, CD_3CN) δ 164.7 (ArC_{11}Ru), 146.6 (ArC_6N), 141.8 (ArCH$_3$), 140.0 (ArCH$_{10}$), 127.1 (ArCH$_5$), 125.2 (ArCH$_9$), 123.8 (MeCN), 122.3 (MeCN), 122.1 (ArCH$_8$), 111.5 (ArCH$_7$), 108.2 (ArCH$_4$), 4.2 (CH$_3$CN), 3.6 (CH$_3$CN); ^{31}P NMR (162 MHz, CD_3CN) δ -144.51 (app quint, *J* = 706.3 Hz); ^{19}F NMR (376 MHz, CD_3CN) δ -72.93 (d, *J* = 706.3 Hz); anal. cald. for $C_{17}H_{19}F_6N_6PRu$: C 36.90, H 3.46, N 15.19; found C 37.05, H 3.55, N 15.26; HRMS (ESI μTOF) m/z calcd for $C_{11}H_{10}N_3Ru$ (phenylpyrazoleRu(MeCN))$^+$ $[M]^+$: 285.9916, found: 285.9926.

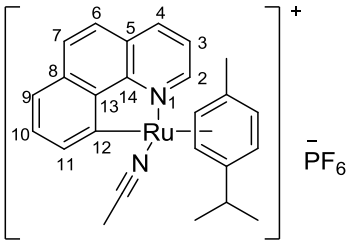
[Benzo[*h*]quinoline ruthenium (*p*-cymene) chloride] (414)[32]



To a flame-dried flask was added $[RuCl_2(p\text{-cymene})]_2$ (310 mg, 0.5 mmol), benzo[*h*]quinoline (170 mg, 1.0 mmol), KOAc (200 mg, 2.0 mmol) and dry MeOH (10 mL, 0.1 M). The reaction flask was

sealed under an atmosphere of Ar and was stirred at rt for 3.5 days. The solvent was removed under reduced pressure and the residue was diluted with minimum amount of EtOAc and the mixture was plugged through a column of oven-dried neutral alumina (Al_2O_3) and eluted with EtOAc. The orange fraction was collected then concentrated *in vacuo* and dried under high vacuum. The desired product was obtained as an orange powder (362 mg, 83%); mpt. (dec.) 193 – 201 °C; ^{1}H NMR (300 MHz, CD_3CN) δ 9.56 (1H, dd, *J* = 4.8, 1.3 Hz, ArH_2), 8.38 (1H, t, *J* = 4.8 Hz, ArH_4), 8.32 (1H, dd, *J* = 8.0, 1.3 Hz, ArH_9), 7.81 (1H, d, *J* = 8.8 Hz, ArH_6), 7.64 (1H, d, *J* = 8.8 Hz, ArH_7), 7.58 – 7.52 (3H, m, ArH_3, ArH_{10} & ArH_{11}), 5.81 – 5.77 (2H, m, cymene Ar*H*), 5.40 (1H, dd, *J* = 5.9, 1.0 Hz, cymene Ar*H*), 5.15 (1H, dd, *J* = 5.9, 1.0 Hz, cymene Ar*H*), 2.34 (1H, hept, *J* = 6.9 Hz, C*H*Me$_2$), 1.98 (3H, s, ArCH_3), 0.85 (4H, d, *J* = 6.9 Hz, CHMeCH_3), 0.71 (3H, d, *J* = 6.9 Hz, CHMeCH_3); ^{13}C NMR (75 MHz, CD_3CN) δ 173.1 (Ar*C*Ru), 156.0 (Ar*C*), 155.3 (Ar*C*H), 141.5 (Ar*C*), 138.0 (Ar*C*H), 134.9 (Ar*C*), 130.3 (Ar*C*H), 130.1 (Ar*C*H), 128.0 (Ar*C*), 124.4 (Ar*C*H), 123.1 (Ar*C*H), 122.8 (Ar*C*H), 105.6 (Ar*C*), 102.7 (Ar*C*), 92.7 (Ar*C*H), 92.3 (Ar*C*H), 88.2 (Ar*C*H), 85.5 (Ar*C*H), 31.8 (*C*HMe$_2$), 22.4 (CHMe*C*H$_3$), 22.1 (CHMe*C*H$_3$), 18.8 (Ar*C*H$_3$); HRMS (ESI μTOF) m/z calcd for $C_{23}H_{22}ClNRu$ $[M+Na]^+$: 472.0379, found: 472.0382.

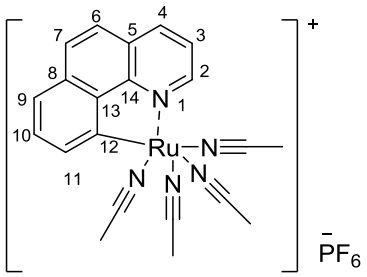
[Benzo[*h*]quinoline ruthenium (*p*-cymene) acetonitrile] hexafluorophosphate (415)



To a flame-dried flask under Ar, was added complex **414** (110 mg, 0.3 mmol), $AgPF_6$ (110 mg, 0.4 mmol) and dry MeCN (2.5 mL) and the reaction was sealed under an atmosphere of Ar. The reaction mixture was stirred at rt for 1 h. The reaction mixture was plugged through a column of oven-dried neutral alumina (Al_2O_3) and eluted with MeCN. The yellow band was collected and concentrated *in vacuo* and afforded the desired product as a yellow powder (145 mg, 97%); mpt. (dec.) 180 – 187 °C; ν_{max} (neat) / cm^{-1}; 3059, 2271, 1567, 1481, 1435; ^{1}H NMR (300 MHz, CD_3CN) δ 9.48 (1H, dd, *J* = 6.7, 1.2 Hz, ArH_2), 8.47 (1H, dd, *J* = 6.7, 1.2 Hz, ArH_4), 8.38 (1H, dd, *J* = 6.9, 1.0 Hz, ArH_9), 7.89 (1H, d, *J* = 8.8 Hz, ArH_6), 7.73 (1H, d, *J* = 8.8 Hz, ArH_7), 7.70 – 7.60 (3H, m, ArH_3, ArH_{10} & ArH_{11}), 6.07 (1H, dd, *J* = 6.1, 1.0 Hz, cymene Ar*H*), 6.01 (1H, d, *J* = 6.1 Hz, cymene Ar*H*), 5.75 (1H, dd, *J* = 6.1, 1.0 Hz, cymene Ar*H*), 5.54 (1H, d, *J* = 6.1 Hz, cymene Ar*H*), 2.38 (1H, hept, *J* = 6.9 Hz, C*H*Me$_2$), 1.97 (3H, s, ArCH_3), 0.87 (3H, d, *J* = 6.9 Hz, CHMeCH_3), 0.83 (3H, d, *J* = 6.9 Hz, CHMeCH_3); ^{13}C NMR (125 MHz, CD_3CN) δ 173.1 (Ar*C*Ru), 156.0 (Ar*C*), 155.3 (Ar*C*H), 141.5 (Ar*C*), 138.0 (Ar*C*H),

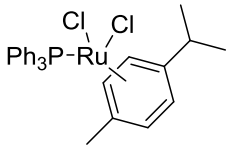
134.9 (Ar*C*), 130.3 (Ar*C*H), 130.1 (Ar*C*H), 128.0 (Ar*C*), 124.4 (Ar*C*H), 123.08 (Ar*C*H), 122.75 (Ar*C*H), 105.57 (Ar*C*), 102.73 (Ar*C*), 92.71 (Ar*C*H), 92.31 (Ar*C*H), 88.16 (Ar*C*H), 85.5 (Ar*C*H), 31.8 (*C*HMe$_2$), 22.4 (CHMe*C*H$_3$), 22.1 (CHMe*C*H$_3$), 18.8 (Ar*C*H$_3$); ^{31}P NMR (162 MHz, CD$_3$CN) δ -144.50 (app quint, *J* = 706.3 Hz); ^{19}F NMR (376 MHz, CD$_3$CN) δ -72.91 (d, *J* = 706.4 Hz); anal. cald. for $C_{26}H_{28}F_6N_2PRu$: C 50.09, H 4.20, N 4.67; found C 50.15, H 4.27, N 4.75; HRMS (ESI µTOF) m/z calcd for $C_{23}H_{22}NRu$ (benzo[*h*]quinolineRu(*p*-cymene))$^+$ [M]$^+$: 414.0796, found: 414.0817.

[Benzo[*h*]quinoline ruthenium tetra acetonitrile] hexafluorophosphate (416)



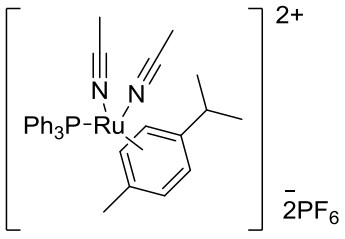
To a flame-dried carousel tube under Ar was added complex **415** (90 mg, 0.2 mmol) and dry MeCN (2 mL) and the tube was sealed under an atmosphere of Ar. The reaction mixture was heated at 85 °C for 6.5 days. The reaction mixture was plugged through a column of oven-dried neutral alumina (Al_2O_3) and eluted with dry MeCN. The orange band was collected and concentrated *in vacuo*. The residue was washed with Et_2O (3 × 10 mL) and removed the solvent *via* cannula filtration. The desired product was afforded as an orange solid (53.2 mg, 61%); mpt. (dec.) 171 – 175 °C; ν_{max} (neat) / cm^{-1}; 2271, 1567, 1481, 1435, 1327, 1194, 1090, 834, 741, 721, 696; ^{1}H NMR (500 MHz, CD$_3$CN) δ 9.18 (1H, dd, *J* = 6.6, 0.8 Hz, Ar*H*$_2$), 8.27 (1H, dd, *J* = 6.6, 0.8 Hz, Ar*H*$_4$), 8.17 (1H, dd, *J* = 5.8, 2.3 Hz, Ar*H*$_9$), 7.84 (1H, d, *J* = 8.8 Hz, Ar*H*$_6$), 7.68 (1H, d, *J* = 8.8 Hz, Ar*H*$_7$), 7.56 – 7.47 (3H, m, Ar*H*$_3$, Ar*H*$_{10}$ & Ar*H*$_{11}$), 1.96 (3H, s, C*H*$_3$CN), 1.91 (6H, s, 2 × C*H*$_3$CN); ^{13}C NMR (125 MHz, CD$_3$CN) δ 181.9 (Ar*C*Ru), 158.5 (Ar*C*$_{14}$), 152.4 (Ar*C*$_2$H), 144.1 (Ar*C*$_5$), 136.6 (Ar*C*$_9$H), 135.7 (Ar*C*$_4$H), 134.1 (Ar*C*), 129.9 (Ar*C*$_6$H), 128.5 (Ar*C*$_{11}$H), 126.7 (Ar*C*), 124.0 (Ar*C*$_7$H), 121.7 (Ar*C*$_3$H), 119.6 (Ar*C*$_{10}$H); ^{31}P NMR (162 MHz, CD$_3$CN) δ -144.49 (app quint, *J* = 706.6 Hz); ^{19}F NMR (376 MHz, CD$_3$CN) δ -73.01 (d, *J* = 706.4 Hz); anal. cald. for $C_{21}H_{20}F_6N_5PRu$: C 42.86, H 3.43, N 11.90; found C 42.96, H 3.50, N 12.055; HRMS (ESI µTOF) m/z calcd for $C_{19}H_{17}N_4Ru$ (benzo[*h*]quinolineRu(MeCN)$_3$)$^+$ [M]$^+$: 403.0496, found: 403.0520.

[Dichloro ruthenium (triphenylphosphine) (*p*-cymene)] (440)[34]



To a flame-dried flask was added $[RuCl_2(p\text{-cymene})]_2$ (300 mg, 0.5 mmol) and PPh_3 (270 mg, 1.0 mmol) in dry dichloromethane (10 mL), the flask was sealed under an atmosphere of Ar. The red mixture was stirred at rt for 2 h. The reaction mixture was concentrated *in vacuo* and then dissolved in minimum amount of dichloromethane and precipitated with *n*-hexane. The precipitate was filtered through fritted funnel and washed with pentane (20 mL). The desired product was afforded as a brown powder (521 mg, 90%); mpt. (dec.) 192 – 198 °C; ν_{max} (neat) / cm^{-1}; 3049, 2988, 2959, 2868, 1588, 1574, 1542, 1502, 1483, 1472, 1460, 1435; ^{1}H NMR (500 MHz, d_8-toluene) δ 8.00 (1H, dd, *J* = 13.1, 5.1 Hz, Ar*H*), 7.03 – 6.98 (3H, m, Ar*H*), 4.75 (2H, d, *J* = 5.5 Hz, cymene Ar*H*), 4.66 (2H, d, *J* = 5.5 Hz, cymene Ar*H*), 2.77 – 2.67 (1H, hept, *J* = 7.0 Hz, C*H*Me_2), 1.62 (3H, s, ArCH_3), 0.86 (3H, s, CHMeCH_3), 0.85 (3H, s, CHMeCH_3); ^{13}C NMR (125 MHz, d_8-toluene) δ 137.7 (PAr*C*H), 137.2 (PAr*C*H), 134.9 (d, *J* = 9.2 Hz, PAr*C*H), 130.0 (PAr*C*H), 94.4 (cymene 2 × Ar*C*), 90.7 (cymene Ar*C*H), 90.6 (cymene Ar*C*H), 86.4 (cymene Ar*C*H), 86.3 (cymene Ar*C*H), 30.3 (*C*HMe2), 21.8 (CHMe*C*H_3), 17.3 (CHMe*C*H_3); ^{31}P NMR (123 MHz, d_8-toluene) δ 22.93 (PPh_3); anal. cald. for $C_{28}H_{29}Cl_2PRu$: C 59.16, H 5.14; found C 59.07, H 5.17; HRMS (ESI µTOF) m/z calcd for $C_{28}H_{29}Cl_2PRu$ (Ru(PPh_3)(*p*-cymene)Cl_2) $[M+Na]^+$: 591.0321, found: 591.0319.

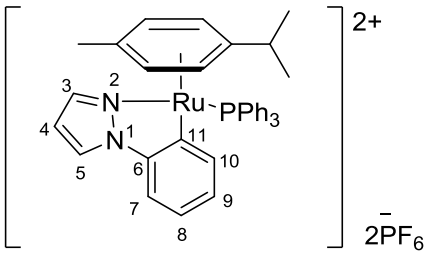
[Ruthenium (*p*-cymene) (triphenylphosphine) diacetonitrile] bis hexafluorophosphate (441)



To a flame-dried flask was added complex **440** (200 mg, 0.4 mmol), $AgPF_6$ (210 mg, 0.8 mmol) and dry MeCN (3.5 mL). The reaction was sealed under an atmosphere of Ar and was allowed to stir at rt for 16 h. The reaction mixture was filtered *via* gravity, and then filtered through a pad of Celite®. The filtrate was concentrated *in vacuo* and dried under the high vacuum. The desired product was afforded as a light green powder (283 mg, 93%); ν_{max} (neat) / cm^{-1}; 2959, 2334, 1482, 1435; ^{1}H NMR (300 MHz, CD_3CN) δ 7.72 – 7.51 (9H, m, PAr*H*), 7.51 – 7.38 (6H, m, PAr*H*), 6.11 (2H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.52 (2H, d, *J* = 6.2 Hz, cymene Ar*H*), 2.89 – 2.73 (1H, hept, *J* = 6.6 Hz,

C*H*Me$_2$), 2.22 (3H, s, C*H*$_3$CN), 2.21(3H, s, C*H*$_3$CN), 1.85 (3H, s, ArC*H*$_3$), 1.27 (3H, s, CHMeC*H*$_3$), 1.25 (3H, s, CHMeC*H*$_3$); ^{13}C NMR (75 MHz, CD$_3$CN) δ 134.7 (d, *J* = 10.3 Hz, PAr*C*H), 133.2 (d, *J* = 2.8 Hz, PAr*C*H), 132.0 (PAr*C*), 130.3 (d, *J* = 10.9 Hz, PAr*C*), 129.8 (PAr*C*H), 129.1 (PAr*C*H), 119.0 (d, *J* = 4.2 Hz, PAr*C*H), 107.3 (PAr*C*H), 93.6 (2 × cymene Ar*C*), 93.5 (2 × Ar*C*H), 92.5 (2 × Ar*C*H), 32.2 (*C*HMe$_2$), 22.1 (CHMe*C*H$_3$), 18.5 (CHMe*C*H$_3$), 4.6 (Ar*C*H$_3$); ^{31}P NMR (122 MHz, CD$_3$CN) δ 33.56 (PPh$_3$), -143.75 (hept, *J* = 706.4 Hz, PF$_6$); ^{19}F NMR (376 MHz, CD$_3$CN) δ -72.87 (d, *J* = 706.4 Hz); anal. cald. for $C_{32}H_{35}F_{12}N_2P_3Ru$: 44.20, H 4.06, N 3.22; found C 38.28, H 3.72, N 3.05; HRMS (ESI μTOF) m/z calcd for $C_{28}H_{29}PRu$ (Ru(PPh$_3$)(*p*-cymene))$^+$ [M]$^+$: 249.0523, found: 249.0502.

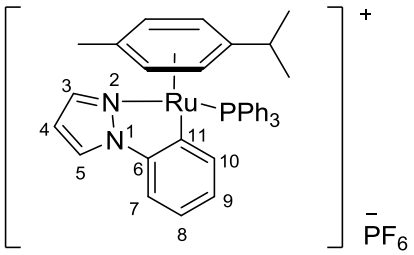
[1-Phenylpyrazole ruthenium (*p*-cymene)(triphenylphosphine)] bishexafluorophosphate (442)



To an oven-dried carousel tube under Ar was added complex **441** (100 mg, 0.1 mmol), K_2CO_3 (40 mg, 0.3 mmol), 1-phenylpyrazole (15 μL, 0.1 mmol) and dry degassed toluene (1.1 mL). The reaction mixture was heated at 80 °C with stirring for 21 h. The reaction mixture was then filtered through a column of oven-dried neutral alumina (Al_2O_3) and eluted with MeCN. The faint blue fraction was collected and the solvent was removed *in vacuo*. Then the residue was precipitated in MeCN and Et$_2$O, and the solvent was removed *via* cannula filtration. The precipitate was washed with Et$_2$O (3 × 5 mL) to afford the product as a yellow powder (16 mg, 14%); ^{1}H NMR (500 MHz, CD$_3$CN) δ 8.17 (1H, s, Ar*H*$_5$), 7.99 – 7.96 (1H, m, Ar*H*$_{10}$), 7.69 (1H, d, *J* = 2.5 Hz, Ar*H*$_3$), 7.43 (3H, t, *J* = 7.0 Hz, PAr*H*), 7.30 (6H, t, *J* = 7.0 Hz, PAr*H*), 7.04 – 6.91 (8H, m, 5 × PAr*H*, Ar*H*$_7$, Ar*H*$_8$ & Ar*H*$_9$), 6.89 (1H, dd, *J* = 7.3, 1.6 Hz, Ar*H*$_7$), 6.36 (1H, app t, *J* = 2.5 Hz, Ar*H*$_4$), 6.03 (1H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.99 (1H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.93 (1H, d, *J* = 6.2 Hz, cymene Ar*H*), 5.39 (1H, d, *J* = 6.2 Hz, cymene Ar*H*), 2.17 – 2.09 (1H, m, C*H*Me$_2$), 1.51 (3H, s, C*H*$_3$), 0.74 (3H, d, *J* = 6.9 Hz, CHMeC*H*$_3$), 0.63 (3H, d, *J* = 6.9 Hz, CHMeC*H*$_3$); ^{13}C NMR (125 MHz, CD$_3$CN) δ 154.0 (Ar*C*N), 153.9 (PAr*C*), 146.2 (2C, d, *J* = 2.2 Hz, PAr*C*H, Ar*C*$_5$H), 143.1 (d, *J* = 3.3 Hz, PAr*C*H), 143.1 (Ar*C*$_{10}$H), 134.6 (d, *J* = 10.2 Hz, PAr*C*H), 131.6 (d, *J* = 2.0 Hz, PAr*C*H), 131.5 (Ar*C*), 131.1 (Ar*C*), 129.1 (d, *J* = 10.0 Hz, PAr*C*H), 127.7 (PAr*C*H), 126.3 (Ar*C*$_3$H), 124.7 (Ar*C*$_9$H), 113.6 (Ar*C*$_8$H), 112.0 (PAr*C*), 111.9 (PAr*C*), 111.4 (Ar*C*$_7$), 110.1 (Ar*C*$_4$H), 96.7 (cymene 2 × Ar*C*H), 96.3 (d, *J* = 2.9 Hz, cymene Ar*C*), 95.1 (d, *J* = 4.0 Hz, cymene Ar*C*), 84.7 (cymene 2 × Ar*C*H), 31.4 (*C*HMe$_2$), 22.4 (CHMe*C*H$_3$), 21.5 (CHMe*C*H$_3$),

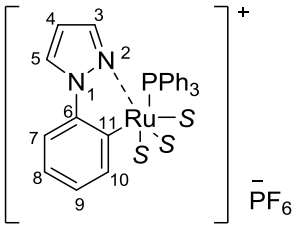
18.7 (Ar*C*H_3); ^{31}P NMR (122 MHz, CD_3CN) δ 45.26 (PPh_3), -143.69 (hept, *J* = 706.5 Hz, PF_6); anal. cald. for $C_{37}H_{36}F_{12}N_2P_3Ru$: C 47.75, H 3.90, N 3.01; found C 55.01, H 4.12, N 3.76; HRMS (ESI μTOF) m/z calcd for $C_{37}H_{36}N_2PRu$ $[M]^{2+}$: 641.1664, found: 641.1689.

[1-Phenylpyrazole ruthenium (*p*-cymene)(triphenylphosphine)] hexafluorophosphate (443)



To a flame-dried flask was added complex **412** (100 mg, 0.2 mmol), PPh_3 (60 mg, 0.2 mmol) and dry degassed MeCN (1.8 mL) and the reaction mixture was sealed under an atmosphere of Ar. The reaction mixture was stirred at rt for 23 days. The reaction mixture was plugged through a long column of oven-dried neutral alumina and eluted with MeCN. The light yellow band was collected. The fractions were concentrated *in vacuo* and precipitated with Et_2O (10 mL). The precipitate was washed with Et_2O (3 × 10 mL) and the solvent was removed *via* cannula filtration and dried under high vacuum. The desired product was afforded as a yellow powder (10 mg, 7%); ν_{max} (neat) / cm^{-1}; 3059, 1482, 1435, 1092, 830, 743, 695; ^{1}H NMR (500 MHz, CD_3CN) δ 8.17 (1H, d, *J* = 1.8 Hz, Ar*H*$_5$), 7.97 (1H, d, *J* = 7.1 Hz, Ar*H*$_{10}$), 7.69 (1H, d, *J* = 2.5 Hz, Ar*H*$_3$), 7.43 (3H, t, *J* = 7.0 Hz, 3 x PAr*H*), 7.30 (6H, t, *J* = 7.0 Hz, 6 x PAr*H*), 7.03 – 6.92 (8H, m, 6 × PAr*H*, Ar*H*$_7$, Ar*H*$_8$ & Ar*H*$_9$), 6.89 (1H, dd, *J* = 7.4, 1.7 Hz, Ar*H*$_7$), 6.36 (1H, app t, *J* = 2.5 Hz Ar*H*$_4$), 6.03 (1H, d, *J* = 6.1 Hz, cymene Ar*H*), 5.99 (1H, d, *J* = 6.4 Hz, cymene Ar*H*), 5.93 (1H, d, *J* = 6.4 Hz, cymene Ar*H*), 5.39 (1H, d, *J* = 6.1 Hz, cymene Ar*H*), 2.17 – 2.10 (1H, m, C*H*Me$_2$), 1.51 (3H, s, ArC*H*$_3$), 0.74 (3H, d, *J* = 6.9 Hz, CHMeC*H*$_3$), 0.63 (3H, d, *J* = 6.9 Hz, CHMeC*H*$_3$); ^{13}C NMR (125 MHz, CD_3CN) δ 154.0 (Ar*C*N), 153.8 (PAr*C*), 146.2 (Ar*C*$_5$H), 143.1 (Ar*C*$_{10}$H), 143.1 (d, *J* = 3.3 Hz, PAr*C*H), 143.1 (PAr*C*H), 134.6 (d, *J* = 10.1 Hz, PAr*C*H), 131.6 (d, *J* = 2.1 Hz, PAr*C*H), 131.5 (PAr*C*), 131.1 (PAr*C*), 129.1 (d, *J* = 10.0 Hz, PAr*C*H), 127.7 (PAr*C*H), 126.3 (Ar*C*$_9$H), 124.7 (Ar*C*$_3$H), 113.6 (Ar*C*$_8$H), 112.0 (d, *J* = 8.7 Hz, PAr*C*), 111.4 (Ar*C*$_7$H), 110.1 (Ar*C*$_4$H), 96.7 (cymene 2 × Ar*C*H), 96.3 (d, *J* = 3.0 Hz, cymene Ar*C*), 95.1 (d, *J* = 4.0 Hz, cymene Ar*C*), 84.7 (cymene 2 × Ar*C*H), 31.4 (*C*HMe$_2$), 22.4 (CHMe*C*H$_3$), 21.5 (CHMe*C*H$_3$), 18.7 (Ar*C*H$_3$); ^{31}P NMR (122 MHz, CD_3CN) δ 45.21 (PPh_3), -143.75 (hept, *J* = 706.2 Hz, PF_6); ^{19}F NMR (376 MHz, CD_3CN) δ -72.91 (d, *J* = 706.5 Hz); HRMS (ESI μTOF) m/z calcd for $C_{37}H_{36}N_2PRu$ $[M]^+$: 641.1664, found: 641.1679.

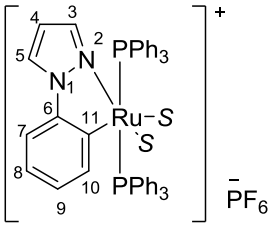
[1-Phenylpyrazole ruthenium (triacetonitrile)(triphenylphosphine)] hexafluorophosphate (445)[35]



S = MeCN

To a flame-dried flask, was added complex **413** (110 mg, 0.2 mmol) and PPh_3 (50 mg, 0.2 mmol) and dry degassed MeCN (17 mL). The flask was sealed and placed under an atmosphere of Ar. The reaction mixture was stirred at rt for 4.5 days. The reaction mixture was plugged through a column of oven-dried neutral alumina (Al_2O_3) eluting with MeCN. All of the fractions were collected and the solvent was removed *in vacuo*. The precipitate was crushed out with addition of Et_2O (10 mL), and the solvent was removed *via* cannula filtration. The precipitate was washed with Et_2O (3 x 10 mL) and the solvent was removed *via* cannula filtration and dried the product *in vacuo*. The desired product was afforded as a white powder (147 mg, 94 %); mpt. (dec.) 170 – 176 °C; ν_{max} (neat) / cm^{-1}; 3022, 2273, 1478, 1437, 1414; ^{1}H NMR (300 MHz, CD_3CN) δ 8.33 (1H, d, *J* = 2.4 Hz, ArH_3), 8.09 – 8.02 (1H, m, ArH_{10}), 7.66 – 7.55 (m, 6H, ArH_7 & PAr*H*), 7.50 – 7.40 (10H, m, PAr*H*), 7.30 (1H, d, *J* = 2.4 Hz, ArH_5), 7.21 – 7.08 (2H, m, ArH_8 & ArH_9), 6.34 (1H, t, *J* = 2.4 Hz, ArH_4); ^{13}C NMR (125 MHz, CD_3CN) δ 165.9 (PAr*C*), 165.2 (Ar*C*Ru), 146.0 (d, *J* = 1.3 Hz, PAr*C*H), 145.3 (2C, ArC_{10}H & PAr*C*), 138.6 (Ar*C*N), 135.4 (ArC_5H), 135.2 (PAr*C*), 134.7 (d, *J* = 11.6 Hz, PAr*C*H), 130.6 (d, *J* = 1.6 Hz, PAr*C*H), 129.5 (d, *J* = 8.6 Hz, PAr*C*H), 128.0 (ArC_3H), 126.3 (d, *J* = 5.3 Hz, PAr*C*H), 124.8 (ArC_9H), 123.8 (ArC_8H), 112.2 (ArC_7H), 108.5 (ArC_4H); ^{31}P NMR (123 MHz, CD_3CN) δ 30.84 (PPh_3), -143.74 (hept, *J* = 706.5 Hz, PF_6); ^{19}F NMR (376 MHz, CD_3CN) δ -72.82 (d, *J* = 706.6 Hz); anal. cald. for $C_{33}H_{31}F_6N_5P_2Ru$: C 51.17, H 4.03, N 9.04; found C 51.06, H 4.08, N 8.88; HRMS (ESI μTOF) m/z calcd for $C_{29}H_{25}N_3PRu$ (phenylpyrazoleRuPPh_3(MeCN))$^+$ $[M]^+$: 548.0832, found: 548.0880.

[1-Phenylpyrazole ruthenium (bisacetonitrile)(triphenylphospine)$_2$] hexafluorophosphate (446)[35]



S = MeCN

To a flame-dried carousel tube was added complex **413** (110 mg, 0.2 mmol) and PPh_3 (100 mg, 0.4 mmol) and dry degassed MeCN (1.8 mL), the tube was sealed and placed under an atmosphere of Ar. The reaction mixture was heated at 85 °C with stirring for 13 days. The reaction mixture was allowed to cool down to rt then plugged through a column of oven-dried neutral alumina (Al_2O_3) and eluted with MeCN (100%). The faint yellow band was collected and solvent removed *in vacuo*. The precipitate was crushed out with addition of Et_2O (10 mL), and the solvent was removed *via* cannula filtration. The precipitate was washed with Et_2O (3 × 5 mL) and the solvent was removed *via* cannula filtration and then dried under high vacuum. The desired product was afforded as a yellow powder (135 mg, 69%); mpt. (dec.) 182 – 187 °C; ν_{max} (neat) / cm^{-1}; 3049, 2269, 1480, 1435; ^{1}H NMR (300 MHz, CD_3CN) δ 7.47 – 7.45 (1H, m, ArH_5), 7.39 – 7.28 (7H, m, ArH_{10} & 6 × PAr*H*), 7.25 – 7.17 (13H, m, ArH_3 & 12 × PAr*H*), 7.11 – 7.03 (12H, m, 12 × PAr*H*), 6.75 – 6.62 (3H, m, ArH_7, ArH_8 & ArH_9), 5.96 (1H, t, *J* = 2.4 Hz, ArH_4), 2.01 (3, s, CH_3CN), 1.96 (3H, s, CH_3CN); ^{13}C NMR (75 MHz, CD_3CN) δ 160.7 (2C, t, *J* = 11.8 Hz, ArC_{11}Ru & PAr*C*), 144.7 (Ar*C*N), 141.8 (ArC_{10}H), 141.3 (ArC_5H), 134.2 (t, *J* = 5.3 Hz, PAr*C*), 132.9 (t, *J* = 19.2 Hz, PAr*C*H), 130.2 (PAr*C*H), 128.8 (t, *J* = 4.4 Hz, PAr*C*H), 127.6 (PAr*C*H/*C*N), 126.2 (ArC_3H), 125.0 (ArC_9H), 121.5 (ArC_8H), 111.4 (ArC_7H), 108.6 (ArC_4H); ^{31}P NMR (123 MHz, CD_3CN) δ 34.06 (2 x PPh_3), -143.76 (hept, *J* = 708.8 Hz, PF_6); ^{19}F NMR (376 MHz, CD_3CN) δ -72.93 (d, *J* = 706.4 Hz); anal. cald. for $C_{49}H_{43}F_6N_4P_3Ru$: C 59.10, H 4.35, N 5.63; found C 59.14, H 5.56, N 4.43; HRMS (ESI μTOF) m/z calcd for $C_{45}H_{37}N_2P_2Ru$ (phenylpyrazoleRu$(PPh_3)_2)^+$ $[M]^+$: 769.1482, found: 769.1464.

5.5. References

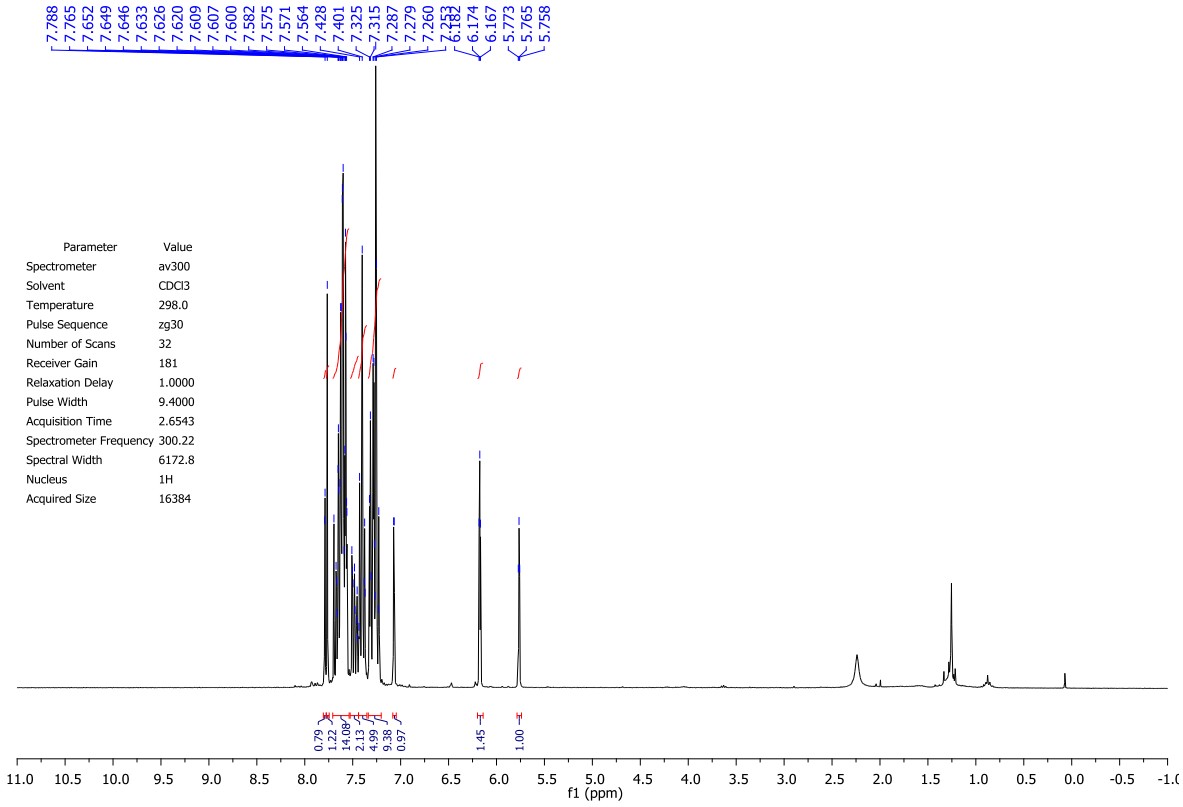
1. O. Saidi, J. Marafie, A. E. W. Ledger, P. M. Liu, M. F. Mahon, G. Kociok-Kohn, M. K. Whittlesey and C. G. Frost, *J. Am. Chem. Soc.*, 2011, **133**, 19298-19301.
2. D. R. Hicks and Fraserre.B, *Synthesis*, 1974, 203-203.
3. L. A. Carpino, J. S. Xia, C. W. Zhang and A. El-Faham, *J. Org. Chem.*, 2004, **69**, 62-71.
4. WO 2007/092435 A2, 2007
5. WO 2007/039741 A1, 2007
6. C. Liu, Q. J. Ni, F. Y. Bao and J. S. Qiu, *Green Chem.*, 2011, **13**, 1260-1266.

7. M. Li and R. M. Hua, *Tetrahedron Lett.*, 2009, **50**, 1478-1481.
8. W. J. Yoo and C. J. Li, *J. Am. Chem. Soc.*, 2006, **128**, 13064-13065.
9. I. Shibata, K. Nakamura, A. Baba and H. Matsuda, *Bull. Chem. Soc. Jpn.*, 1989, **62**, 853-859.
10. T. Kochi, A. Tazawa, K. Honda and F. Kakiuchi, *Chem. Lett.*, 2011, **40**, 1018-1020.
11. M. Z. Li and H. B. Ge, *Org. Lett.*, 2010, **12**, 3464-3467.
12. M. D. Konieczynska, C. Dai and C. R. J. Stephenson, *Org. Biomol. Chem.*, 2012, **10**, 4509-4511.
13. G. Wang, Q. Y. Yu, J. Wang, S. Wang, S. Y. Chen and X. Q. Yu, *RSC Adv.*, 2013, **3**, 21306-21310.
14. K. Higuchi, T. Yamashina, K. Ishikawa and H. Hirata, *J. Jpn. Oil Chem. Soc.*, 1987, **36**, 16-20.
15. Q. Zhang, F. Yang and Y. J. Wu, *Chem. Commun.*, 2013, **49**, 6837-6839.
16. E. Nyfeler and P. Renaud, *Org. Lett.*, 2008, **10**, 985-988.
17. M. Winkler, D. Meischler and N. Klempier, *Adv. Synth. Catal.*, 2007, **349**, 1475-1480.
18. D. A. Tocher, R. O. Gould, T. A. Stephenson, M. A. Bennett, J. P. Ennett, T. W. Matheson, L. Sawyer and V. K. Shah, *J. Chem. Soc. Dalton Trans.*, 1983, 1571-1581.
19. R. F. Borch and A. I. Hassid, *J. Org. Chem.*, 1972, **37**, 1673-1674.
20. Y. Iso, E. Grajkowska, J. T. Wroblewski, J. Davis, N. E. Goeders, K. M. Johnson, S. Sanker, B. L. Roth, W. Tueckmantel and A. P. Kozikowski, *J. Med. Chem.*, 2006, **49**, 1080-1100.
21. A. Correa and C. Bolm, *Adv. Synth. Catal.*, 2007, **349**, 2673-2676.
22. P. Lopezalvarado, C. Avendano and J. C. Menendez, *J. Org. Chem.*, 1995, **60**, 5678-5682.
23. T. Asaumi, N. Chatani, T. Matsuo, F. Kakiuchi and S. Murai, *J. Org. Chem.*, 2003, **68**, 7538-7540.
24. K. Swapna, A. V. Kumar, V. P. Reddy and K. R. Rao, *J. Org. Chem.*, 2009, **74**, 7514-7517.
25. M. Taillefer, N. Xia and A. Ouali, *Angew. Chem. Int. Ed.*, 2007, **46**, 934-936.
26. A. Y. Lebedev, A. S. Khartulyari and A. Z. Voskoboynikov, *J. Org. Chem.*, 2005, **70**, 596-602.
27. M. A. Khan and J. B. Polya, *J. Chem. Soc. Org.*, 1970, 85-91.
28. Y. C. Teo, F. F. Yong, C. Y. Poh, Y. K. Yan and G. L. Chua, *Chem. Commun.*, 2009, 6258-6260.
29. P. M. Liu and C. G. Frost, *Org. Lett.*, 2013, **15**, 5862-5865.
30. X. Zhao, E. Dimitrijevic and V. M. Dong, *J. Am. Chem. Soc.*, 2009, **131**, 3466-3467.
31. E. F. Flegeau, C. Bruneau, P. H. Dixneuf and A. Jutand, *J. Am. Chem. Soc.*, 2011, **133**, 10161-10170.
32. B. Li, T. Roisnel, C. Darcel and P. H. Dixneuf, *Dalton Trans.*, 2012, **41**, 10934-10937.
33. I. Fabre, N. von Wolff, G. Le Duc, E. F. Flegeau, C. Bruneau, P. H. Dixneuf and A. Jutand, *Chem. Eur. J.*, 2013, **19**, 7595-7604.
34. E. E. Joslin, C. L. McMullin, T. B. Gunnoe, T. R. Cundari, M. Sabat and W. H. Myers, *Inorg. Chem.*, 2012, **51**, 4791-4801.
35. L. Leyva, C. Sirlin, L. Rubio, C. Franco, R. Le Lagadec, J. Spencer, P. Bischoff, C. Gaiddon, J. P. Loeffler and M. Pfeffer, *Eur. J. Inorg. Chem.*, 2007, 3055-3066.

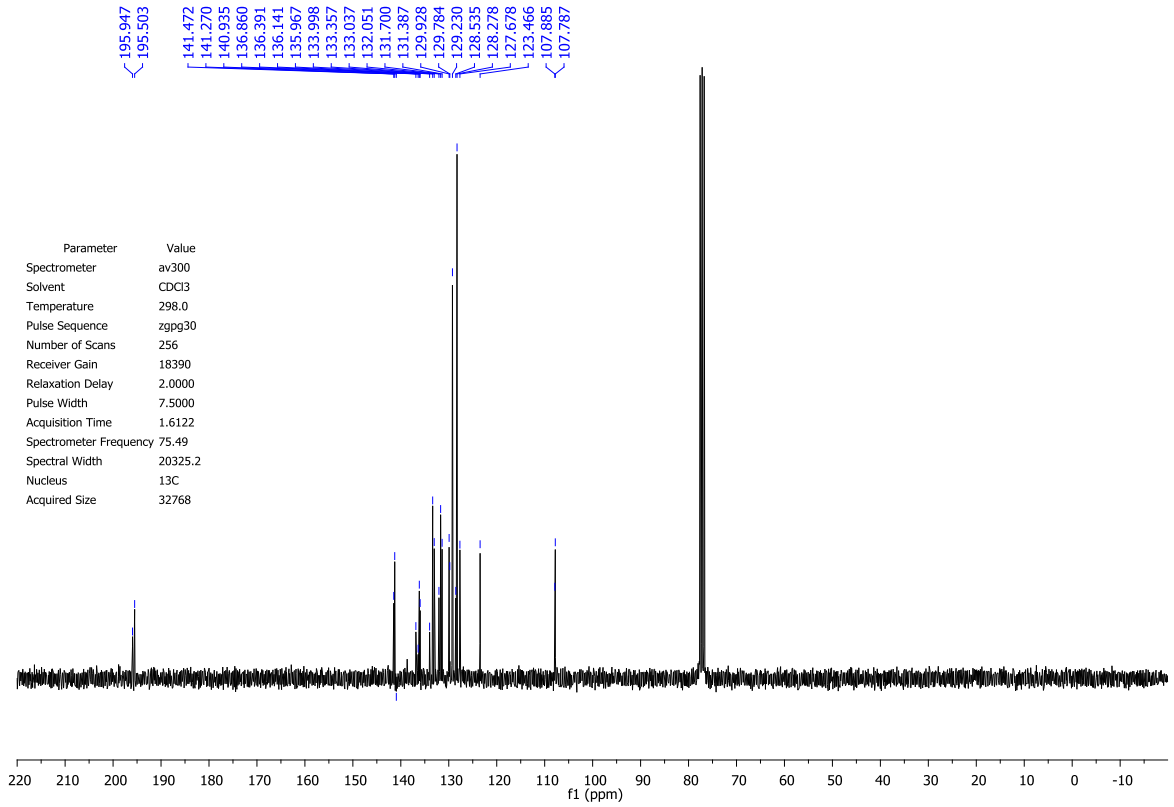
Chapter 6. Appendix

6.1. ^{1}H and ^{13}C NMR spectra

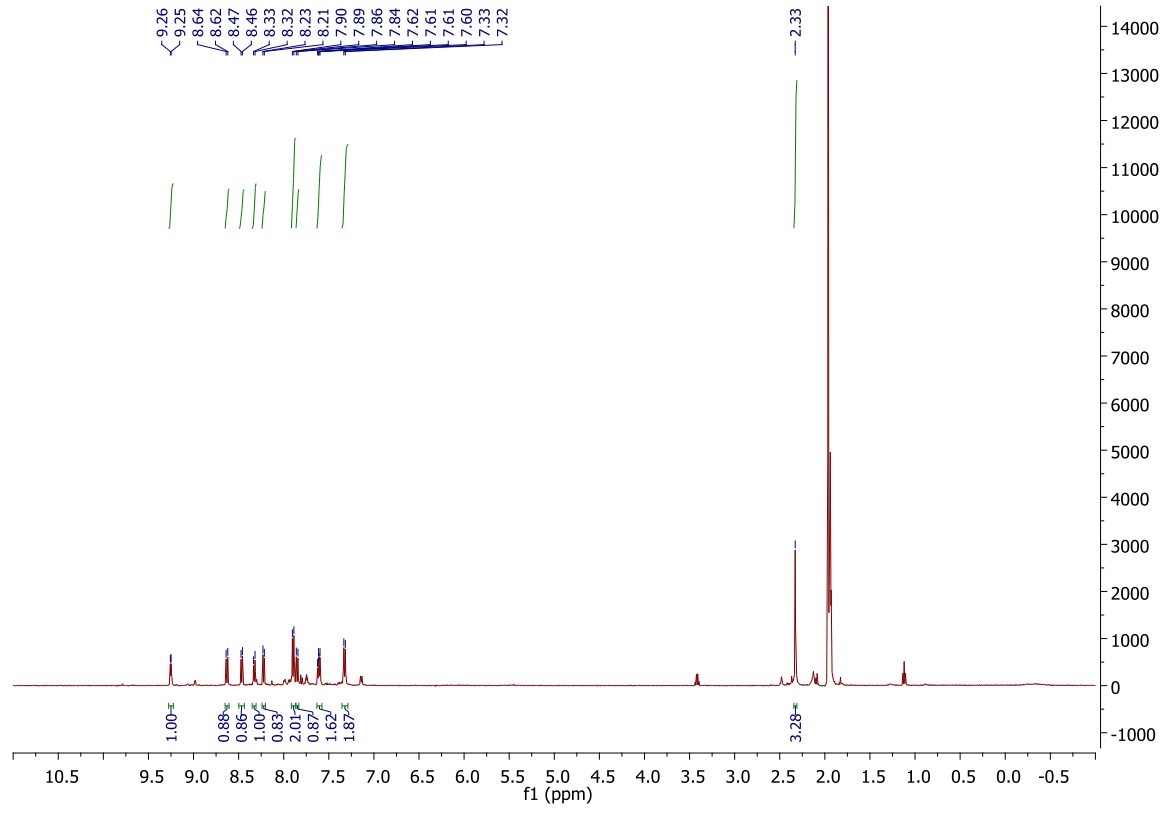
^{1}H NMR spectrum of **370a**



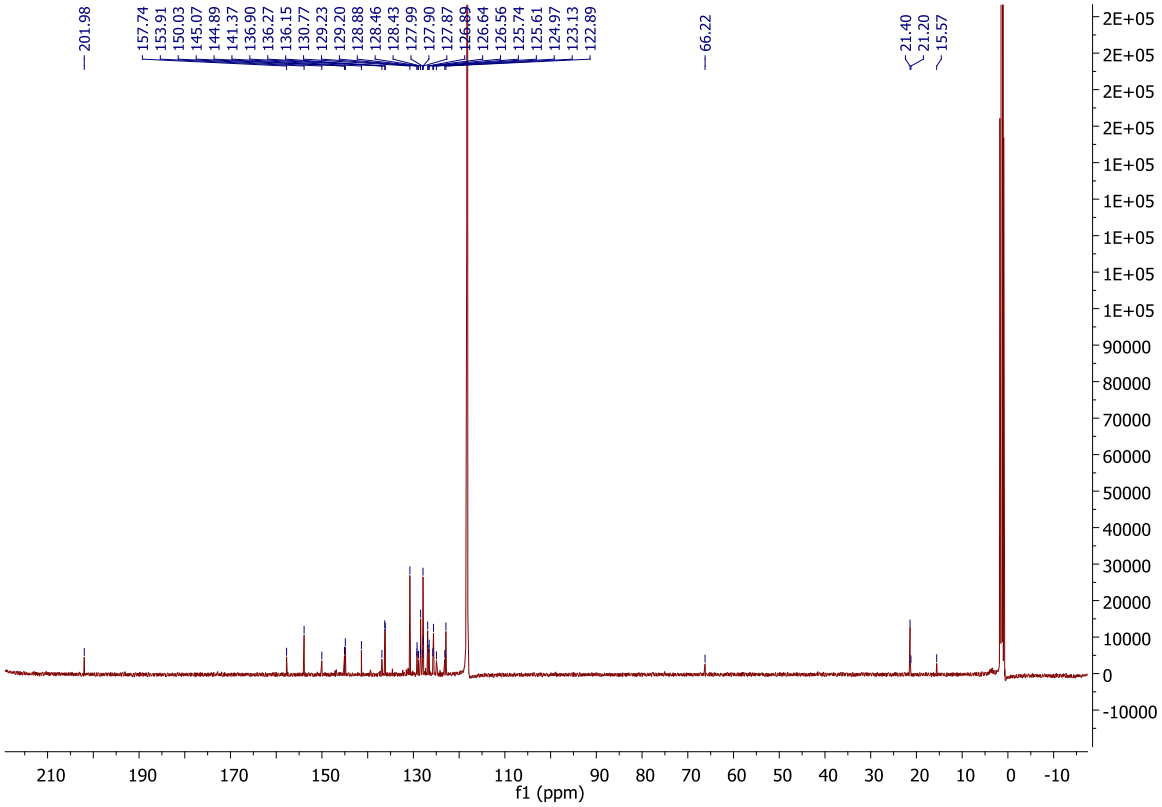
^{13}C NMR spectrum of **370a**



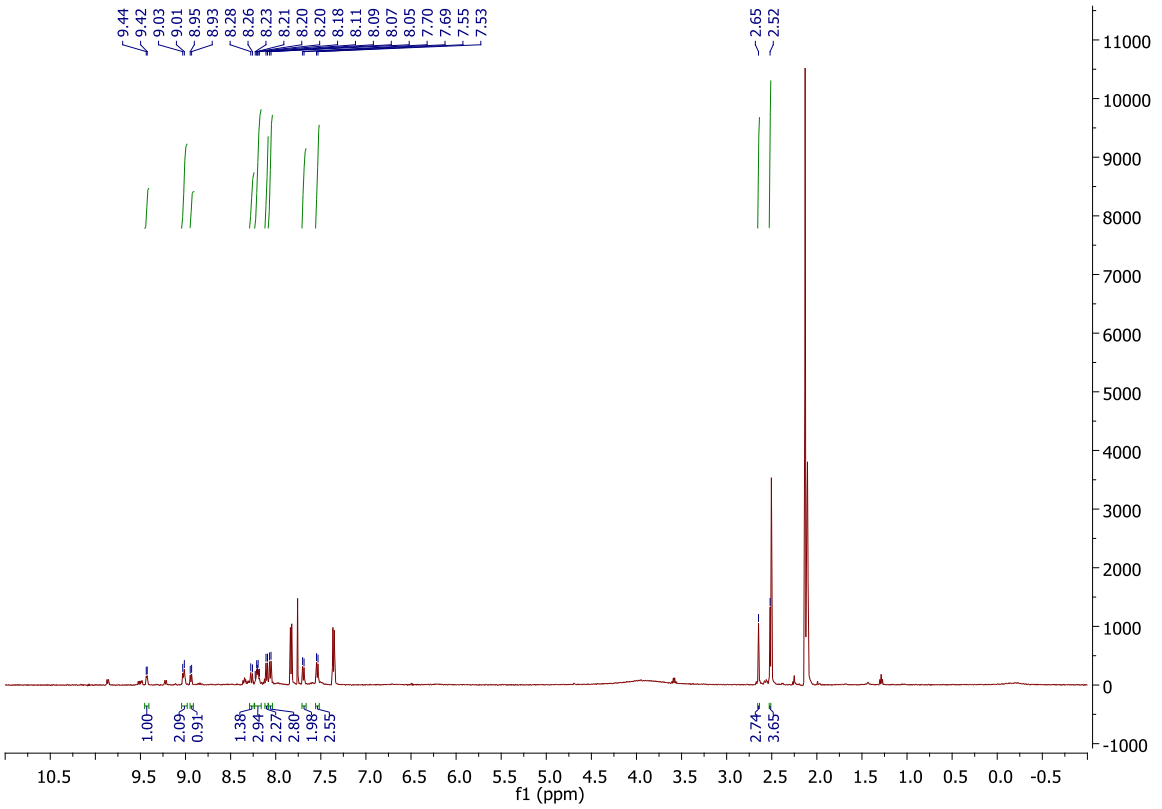
^{1}H NMR spectrum of **423**



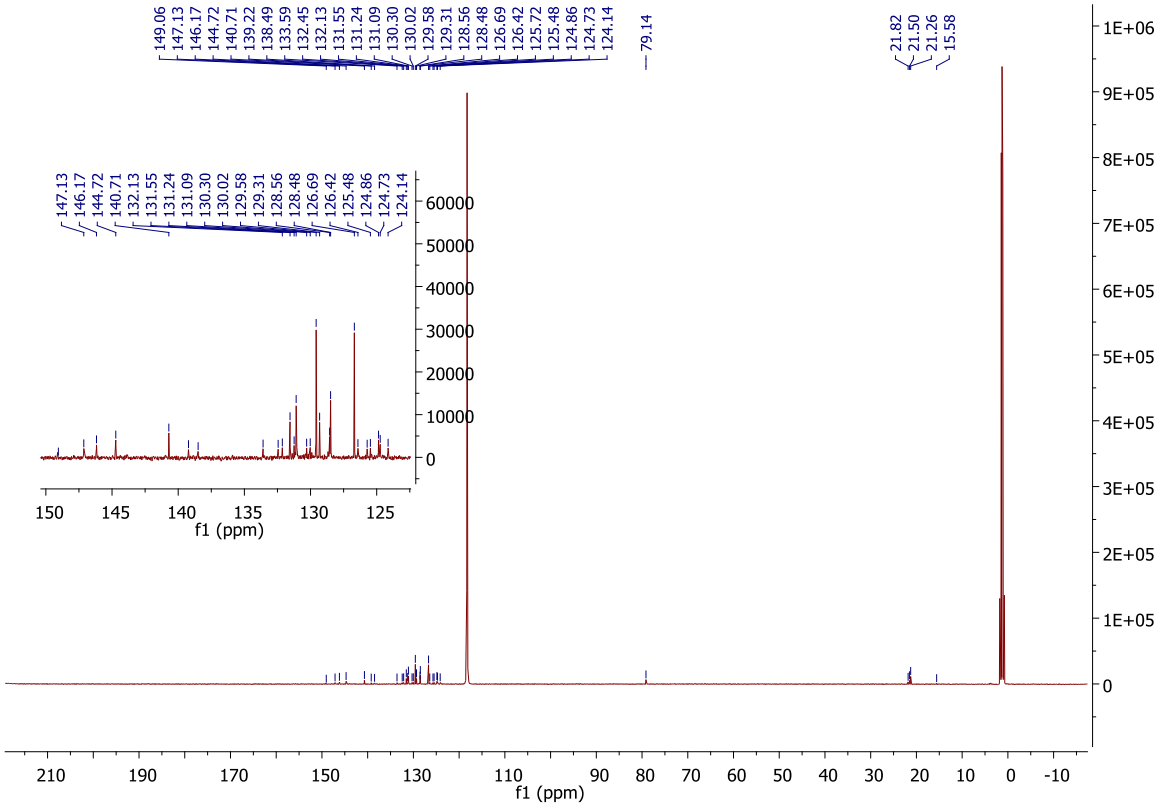
^{13}C NMR spectrum of **423**

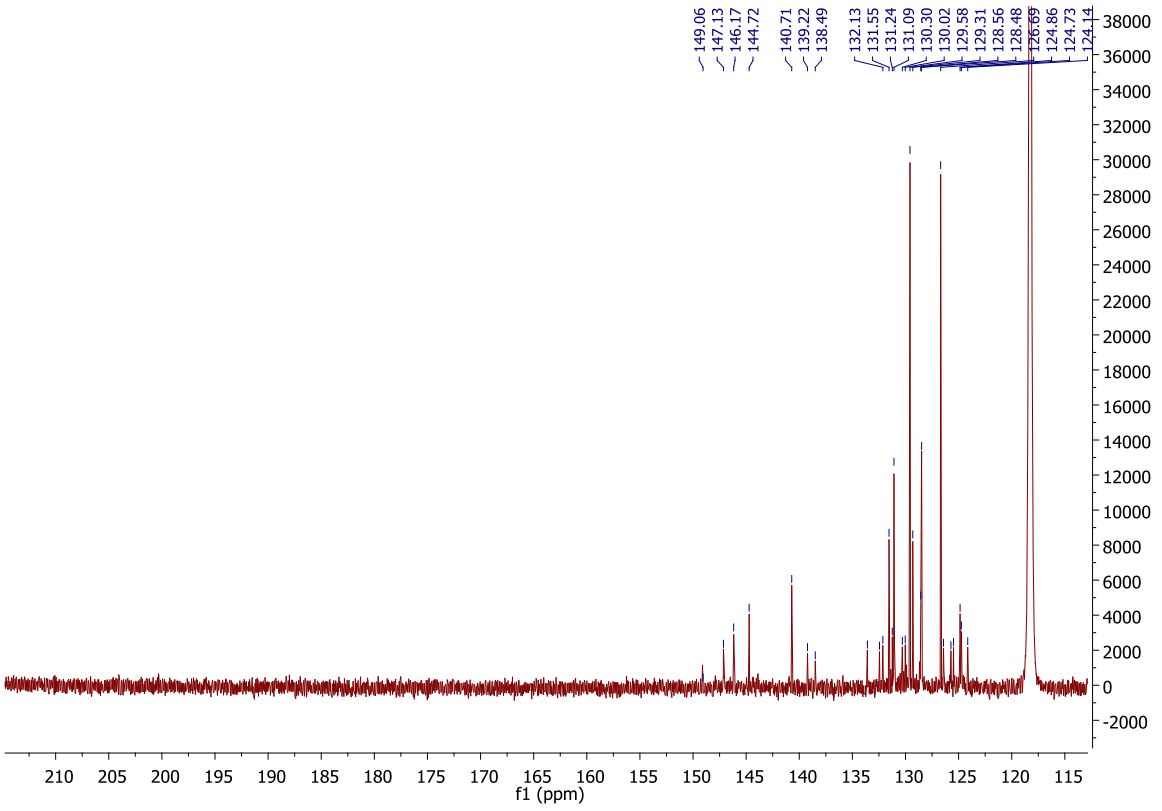


^{1}H NMR spectrum of **424** after silica plug

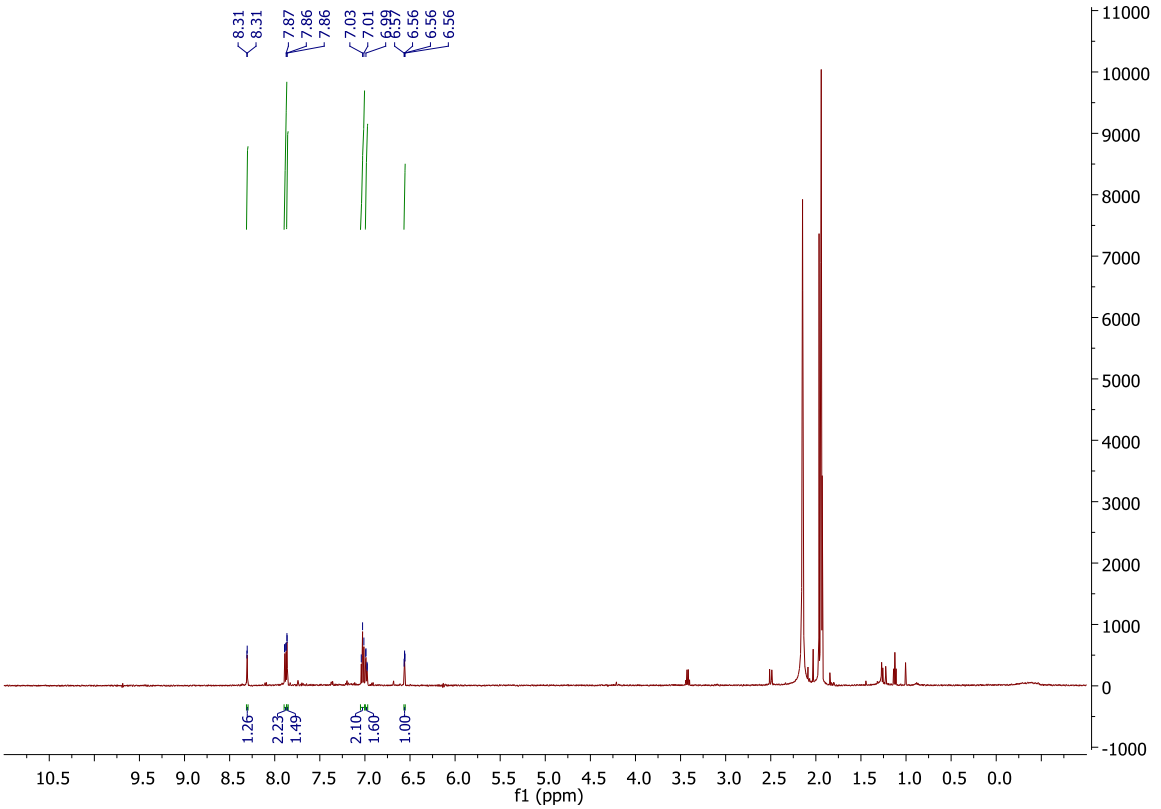


^{13}C NMR spectra of **424** after silica plug

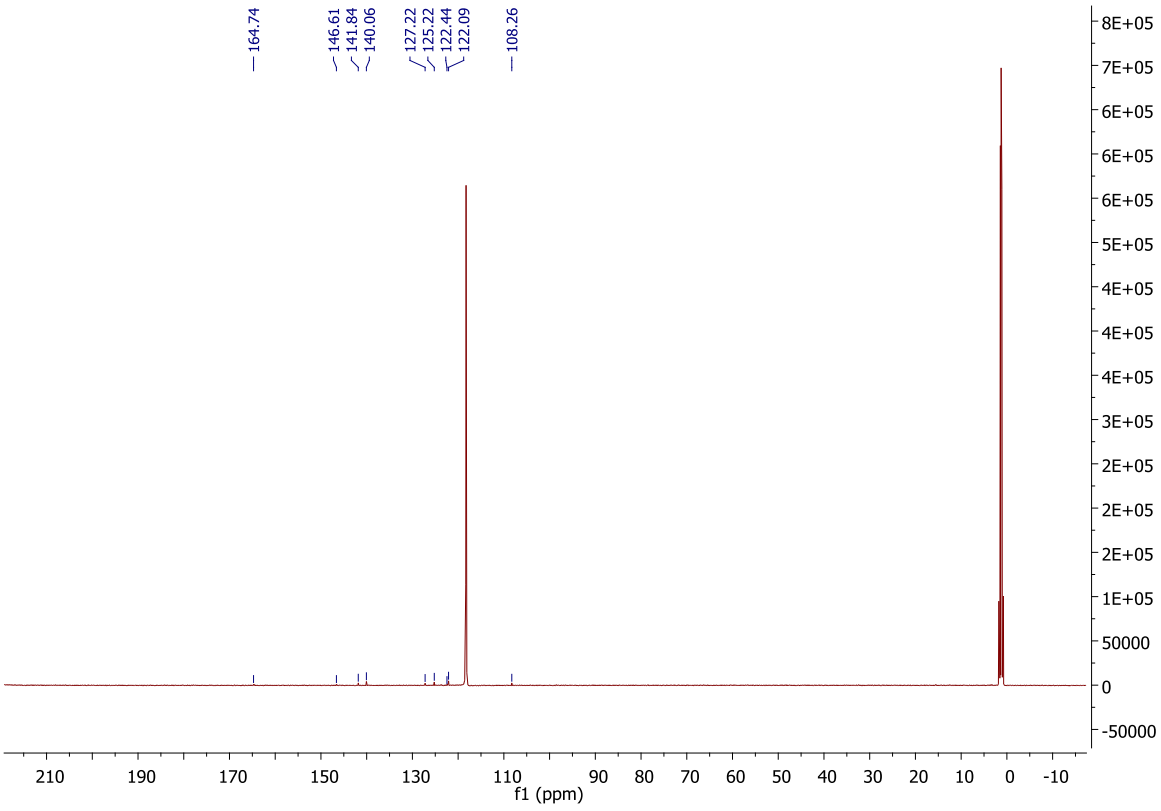


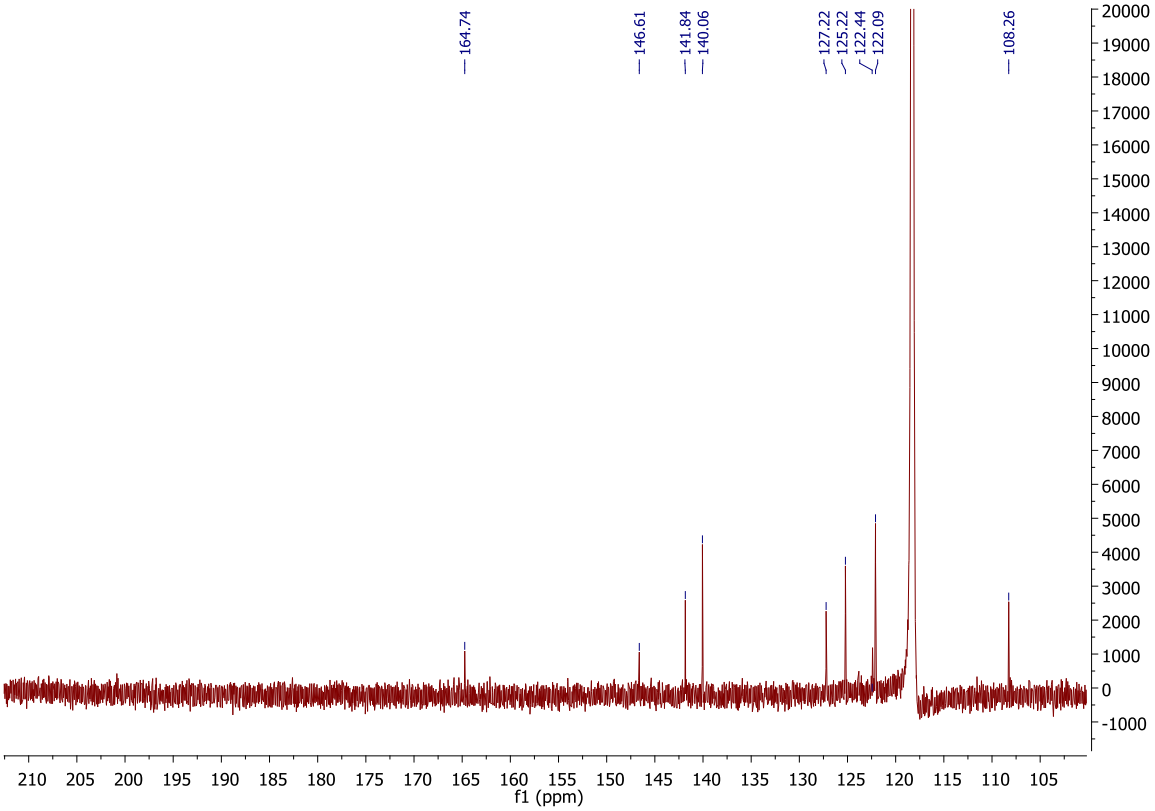


^{1}H NMR spectrum of **438** after silica plug



^{13}C NMR spectra of **438** after silica plug





6.2. X-ray crystal structures

337b

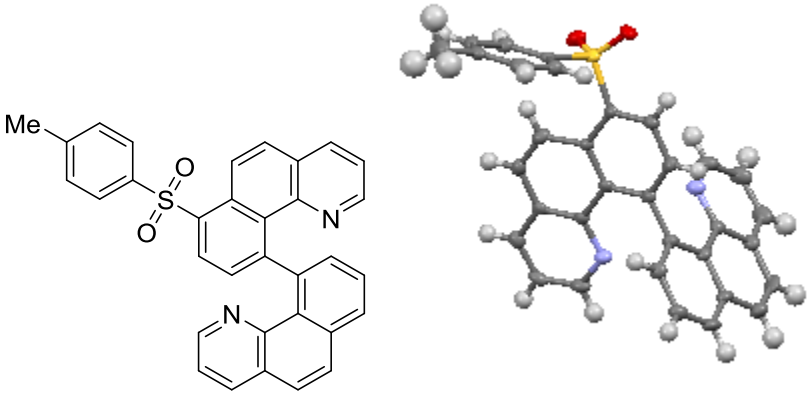


Table 1. Crystal data and structure refinement for p12cgf1.

Identification code	p12cgf1
Empirical formula	C33 H22 N2 O2 S
Formula weight	510.59
Temperature	150(2) K
Wavelength	0.71073 A

Crystal system, space group	Triclinic, P $\bar{1}$
Unit cell dimensions	a = 8.8156(11) A alpha = 113.232(13) deg. b = 12.4382(14) A beta = 93.798(12) deg. c = 13.100(2) A gamma = 106.263(11) deg.
Volume	1241.4(3) A^3
Z, Calculated density	2, 1.366 Mg/m^3
Absorption coefficient	0.166 mm^-1
F(000)	532
Crystal size	0.20 x 0.15 x 0.10 mm
Theta range for data collection	3.06 to 25.34 deg.
Limiting indices	-10<=h<=10, -14<=k<=14, -15<=l<=14
Reflections collected / unique	6294 / 4394 [R(int) = 0.0354]
Completeness to theta = 25.34	96.7 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9836 and 0.9676
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	4394 / 0 / 344
Goodness-of-fit on F^2	0.923
Final R indices [I>2sigma(I)]	R1 = 0.0621, wR2 = 0.1100
R indices (all data)	R1 = 0.1249, wR2 = 0.1207
Largest diff. peak and hole	0.387 and -0.232 e.A^-3

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (A^2 x 10^3) for p12cgf1.
U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

	x	y	z	U(eq)
S(1)	5919(1)	2061(1)	6988(1)	26(1)
O(1)	7537(3)	2119(2)	7354(2)	33(1)
O(2)	5339(3)	1673(2)	5796(2)	32(1)
N(1)	-710(3)	-1643(3)	7313(3)	26(1)
N(2)	2312(3)	-2944(3)	6398(3)	30(1)
C(1)	5831(4)	3570(3)	7747(3)	22(1)
C(2)	6499(4)	4220(4)	8897(3)	28(1)
C(3)	6518(4)	5428(4)	9470(4)	34(1)
C(4)	5914(4)	6017(4)	8913(4)	30(1)
C(5)	5987(5)	7343(4)	9529(4)	50(1)
C(6)	5243(4)	5346(4)	7765(4)	33(1)
C(7)	5190(4)	4113(4)	7165(3)	28(1)
C(8)	4591(4)	1049(3)	7448(3)	20(1)
C(9)	2878(4)	679(3)	7169(3)	19(1)
C(10)	2069(4)	1237(3)	6626(3)	26(1)
C(11)	444(4)	856(4)	6343(3)	27(1)
C(12)	-544(4)	-136(3)	6554(3)	21(1)
C(13)	-2234(4)	-593(4)	6202(3)	29(1)
C(14)	-3117(4)	-1548(4)	6410(3)	29(1)
C(15)	-2307(4)	-2024(4)	6983(3)	31(1)
C(16)	178(4)	-674(3)	7117(3)	19(1)
C(33)	1508(4)	-2833(4)	8160(3)	24(1)
C(17)	1933(4)	-234(3)	7480(3)	21(1)
C(18)	2712(4)	-692(3)	8123(3)	21(1)
C(19)	4382(4)	-248(3)	8421(3)	26(1)
C(20)	5314(4)	609(3)	8079(3)	25(1)
C(21)	1863(4)	-1531(4)	8636(3)	23(1)
C(22)	1491(4)	-935(4)	9681(3)	29(1)
C(23)	799(4)	-1585(4)	10291(3)	30(1)
C(24)	503(4)	-2839(4)	9863(4)	33(1)
C(25)	837(4)	-3484(4)	8798(3)	27(1)
C(26)	485(5)	-4801(4)	8339(4)	39(1)
C(27)	734(4)	-5463(4)	7309(4)	39(1)
C(28)	1359(4)	-4864(4)	6610(4)	31(1)
C(29)	1588(4)	-5525(4)	5506(4)	42(1)
C(30)	2144(5)	-4905(4)	4884(4)	41(1)
C(31)	2486(4)	-3620(4)	5352(4)	37(1)
C(32)	1754(4)	-3558(4)	7036(3)	24(1)

Table 3. Bond lengths [A] for p12cgf1.

S(1)-O(2)	1.447(3)
S(1)-O(1)	1.447(2)
S(1)-C(1)	1.770(4)
S(1)-C(8)	1.785(3)
N(1)-C(15)	1.333(4)
N(1)-C(16)	1.369(4)
N(2)-C(31)	1.341(5)
N(2)-C(32)	1.368(4)
C(1)-C(7)	1.386(4)
C(1)-C(2)	1.387(5)
C(2)-C(3)	1.385(5)
C(2)-H(2)	0.9500
C(3)-C(4)	1.392(5)
C(3)-H(3)	0.9500
C(4)-C(6)	1.387(5)
C(4)-C(5)	1.503(5)
C(5)-H(5A)	0.9800
C(5)-H(5B)	0.9800
C(5)-H(5C)	0.9800
C(6)-C(7)	1.406(5)
C(6)-H(6)	0.9500
C(7)-H(7)	0.9500
C(8)-C(20)	1.367(4)
C(8)-C(9)	1.425(4)
C(9)-C(17)	1.425(4)
C(9)-C(10)	1.447(4)
C(10)-C(11)	1.351(5)
C(10)-H(10)	0.9500
C(11)-C(12)	1.434(5)
C(11)-H(11)	0.9500
C(12)-C(16)	1.400(4)
C(12)-C(13)	1.409(5)
C(13)-C(14)	1.364(5)
C(13)-H(13)	0.9500
C(14)-C(15)	1.392(5)
C(14)-H(14)	0.9500
C(15)-H(15)	0.9500
C(16)-C(17)	1.463(5)
C(33)-C(21)	1.415(5)
C(33)-C(25)	1.426(5)
C(33)-C(32)	1.460(5)
C(17)-C(18)	1.424(4)
C(18)-C(19)	1.387(4)
C(18)-C(21)	1.511(5)
C(19)-C(20)	1.396(5)
C(19)-H(19)	0.9500
C(20)-H(20)	0.9500
C(21)-C(22)	1.387(5)
C(22)-C(23)	1.401(5)
C(22)-H(22)	0.9500
C(23)-C(24)	1.371(5)
C(23)-H(23)	0.9500
C(24)-C(25)	1.407(5)
C(24)-H(24)	0.9500
C(25)-C(26)	1.434(5)

C(26)-C(27)	1.346(5)
C(26)-H(26)	0.9500
C(27)-C(28)	1.439(5)
C(27)-H(27)	0.9500
C(28)-C(29)	1.415(5)
C(28)-C(32)	1.419(5)
C(29)-C(30)	1.355(5)
C(29)-H(29)	0.9500
C(30)-C(31)	1.397(5)
C(30)-H(30)	0.9500
C(31)-H(31)	0.9500

Table 4. Bond angles [deg] for p12cgf1.

O(2)-S(1)-O(1)	118.84(15)
O(2)-S(1)-C(1)	107.98(17)
O(1)-S(1)-C(1)	106.36(17)
O(2)-S(1)-C(8)	108.85(16)
O(1)-S(1)-C(8)	106.73(16)
C(1)-S(1)-C(8)	107.59(16)
C(15)-N(1)-C(16)	117.0(3)
C(31)-N(2)-C(32)	117.6(3)
C(7)-C(1)-C(2)	121.0(4)
C(7)-C(1)-S(1)	119.2(3)
C(2)-C(1)-S(1)	119.7(3)
C(3)-C(2)-C(1)	119.3(4)
C(3)-C(2)-H(2)	120.3
C(1)-C(2)-H(2)	120.3
C(2)-C(3)-C(4)	121.5(4)
C(2)-C(3)-H(3)	119.2
C(4)-C(3)-H(3)	119.2
C(6)-C(4)-C(3)	118.2(4)
C(6)-C(4)-C(5)	120.4(4)
C(3)-C(4)-C(5)	121.4(4)
C(4)-C(5)-H(5A)	109.5
C(4)-C(5)-H(5B)	109.5
H(5A)-C(5)-H(5B)	109.5
C(4)-C(5)-H(5C)	109.5
H(5A)-C(5)-H(5C)	109.5
H(5B)-C(5)-H(5C)	109.5
C(4)-C(6)-C(7)	121.5(4)
C(4)-C(6)-H(6)	119.3
C(7)-C(6)-H(6)	119.3
C(1)-C(7)-C(6)	118.5(4)
C(1)-C(7)-H(7)	120.8
C(6)-C(7)-H(7)	120.8
C(20)-C(8)-C(9)	120.7(3)
C(20)-C(8)-S(1)	115.9(3)
C(9)-C(8)-S(1)	123.5(3)
C(8)-C(9)-C(17)	118.6(3)
C(8)-C(9)-C(10)	122.3(3)
C(17)-C(9)-C(10)	119.0(3)
C(11)-C(10)-C(9)	121.6(3)
C(11)-C(10)-H(10)	119.2
C(9)-C(10)-H(10)	119.2
C(10)-C(11)-C(12)	120.9(4)
C(10)-C(11)-H(11)	119.6
C(12)-C(11)-H(11)	119.6
C(16)-C(12)-C(13)	118.9(3)
C(16)-C(12)-C(11)	119.7(3)
C(13)-C(12)-C(11)	121.4(4)
C(14)-C(13)-C(12)	119.2(4)
C(14)-C(13)-H(13)	120.4
C(12)-C(13)-H(13)	120.4
C(13)-C(14)-C(15)	118.4(3)
C(13)-C(14)-H(14)	120.8
C(15)-C(14)-H(14)	120.8
N(1)-C(15)-C(14)	124.8(4)
N(1)-C(15)-H(15)	117.6

C(14)-C(15)-H(15)	117.6
N(1)-C(16)-C(12)	121.8(3)
N(1)-C(16)-C(17)	117.9(3)
C(12)-C(16)-C(17)	120.3(3)
C(21)-C(33)-C(25)	118.5(4)
C(21)-C(33)-C(32)	123.7(3)
C(25)-C(33)-C(32)	117.8(3)
C(18)-C(17)-C(9)	119.6(3)
C(18)-C(17)-C(16)	122.2(3)
C(9)-C(17)-C(16)	118.2(3)
C(19)-C(18)-C(17)	119.0(3)
C(19)-C(18)-C(21)	115.5(3)
C(17)-C(18)-C(21)	125.1(3)
C(18)-C(19)-C(20)	121.6(4)
C(18)-C(19)-H(19)	119.2
C(20)-C(19)-H(19)	119.2
C(8)-C(20)-C(19)	120.4(3)
C(8)-C(20)-H(20)	119.8
C(19)-C(20)-H(20)	119.8
C(22)-C(21)-C(33)	119.4(3)
C(22)-C(21)-C(18)	115.4(3)
C(33)-C(21)-C(18)	125.1(3)
C(21)-C(22)-C(23)	121.7(4)
C(21)-C(22)-H(22)	119.1
C(23)-C(22)-H(22)	119.1
C(24)-C(23)-C(22)	119.7(4)
C(24)-C(23)-H(23)	120.1
C(22)-C(23)-H(23)	120.1
C(23)-C(24)-C(25)	120.4(4)
C(23)-C(24)-H(24)	119.8
C(25)-C(24)-H(24)	119.8
C(24)-C(25)-C(33)	120.2(4)
C(24)-C(25)-C(26)	120.3(4)
C(33)-C(25)-C(26)	119.5(4)
C(27)-C(26)-C(25)	122.4(4)
C(27)-C(26)-H(26)	118.8
C(25)-C(26)-H(26)	118.8
C(26)-C(27)-C(28)	120.6(4)
C(26)-C(27)-H(27)	119.7
C(28)-C(27)-H(27)	119.7
C(29)-C(28)-C(32)	118.2(4)
C(29)-C(28)-C(27)	122.7(4)
C(32)-C(28)-C(27)	119.0(4)
C(30)-C(29)-C(28)	119.6(4)
C(30)-C(29)-H(29)	120.2
C(28)-C(29)-H(29)	120.2
C(29)-C(30)-C(31)	119.0(4)
C(29)-C(30)-H(30)	120.5
C(31)-C(30)-H(30)	120.5
N(2)-C(31)-C(30)	124.0(4)
N(2)-C(31)-H(31)	118.0
C(30)-C(31)-H(31)	118.0
N(2)-C(32)-C(28)	121.6(4)
N(2)-C(32)-C(33)	117.9(3)
C(28)-C(32)-C(33)	120.5(3)

Symmetry transformations used to generate equivalent atoms:

Table 5. Anisotropic displacement parameters (A^2 x 10^3) for p12cgf1. The anisotropic displacement factor exponent takes the form:
-2 pi^2 [h^2 a*^2 U11 + ... + 2 h k a* b* U12]

	U11	U22	U33	U23	U13	U12
S(1)	25(1)	19(1)	33(1)	12(1)	11(1)	5(1)
O(1)	20(1)	33(2)	49(2)	20(2)	13(1)	8(1)
O(2)	41(2)	26(2)	25(2)	11(2)	12(1)	6(1)
N(1)	25(2)	23(2)	29(2)	11(2)	8(2)	4(2)
N(2)	30(2)	28(2)	29(2)	11(2)	10(2)	6(2)
C(1)	18(2)	22(2)	28(3)	13(2)	8(2)	3(2)
C(2)	26(2)	29(2)	29(3)	14(2)	6(2)	7(2)
C(3)	32(2)	27(3)	32(3)	6(2)	8(2)	1(2)
C(4)	25(2)	24(2)	41(3)	14(2)	16(2)	7(2)
C(5)	57(3)	28(3)	63(4)	15(3)	24(3)	16(2)
C(6)	28(2)	26(2)	53(3)	25(3)	12(2)	7(2)
C(7)	28(2)	24(2)	30(3)	12(2)	5(2)	3(2)
C(8)	24(2)	14(2)	21(2)	7(2)	9(2)	6(2)
C(9)	22(2)	14(2)	16(2)	4(2)	7(2)	3(2)
C(10)	29(2)	20(2)	24(2)	10(2)	3(2)	2(2)
C(11)	32(2)	25(2)	25(3)	11(2)	8(2)	12(2)
C(12)	23(2)	17(2)	20(2)	4(2)	10(2)	8(2)
C(13)	28(2)	28(2)	25(3)	6(2)	5(2)	11(2)
C(14)	18(2)	29(2)	27(3)	3(2)	5(2)	4(2)
C(15)	27(2)	25(2)	33(3)	9(2)	12(2)	1(2)
C(16)	22(2)	18(2)	16(2)	5(2)	9(2)	6(2)
C(33)	21(2)	23(2)	27(3)	13(2)	3(2)	3(2)
C(17)	24(2)	22(2)	17(2)	8(2)	9(2)	9(2)
C(18)	26(2)	15(2)	21(2)	5(2)	8(2)	7(2)
C(19)	30(2)	18(2)	30(3)	11(2)	6(2)	7(2)
C(20)	22(2)	24(2)	30(3)	11(2)	8(2)	7(2)
C(21)	23(2)	25(2)	21(2)	11(2)	6(2)	6(2)
C(22)	30(2)	22(2)	28(3)	7(2)	5(2)	6(2)
C(23)	27(2)	38(3)	26(3)	15(2)	8(2)	9(2)
C(24)	26(2)	43(3)	38(3)	28(3)	13(2)	7(2)
C(25)	21(2)	31(2)	34(3)	22(2)	7(2)	3(2)
C(26)	38(2)	39(3)	50(3)	30(3)	17(2)	12(2)
C(27)	41(3)	18(2)	62(3)	24(3)	11(2)	5(2)
C(28)	25(2)	22(2)	40(3)	12(2)	8(2)	4(2)
C(29)	36(2)	24(3)	55(3)	9(3)	12(2)	6(2)
C(30)	37(2)	38(3)	34(3)	5(3)	13(2)	8(2)
C(31)	33(2)	36(3)	35(3)	13(2)	14(2)	3(2)
C(32)	19(2)	27(2)	27(3)	13(2)	4(2)	7(2)

Table 6. Hydrogen coordinates (x 10^4) and isotropic displacement parameters (A^2 x 10^3) for p12cgf1.

	x	y	z	U(eq)
H(2)	6938	3840	9288	34
H(3)	6953	5866	10261	41
H(5A)	6832	7875	9321	74
H(5B)	6231	7603	10349	74
H(5C)	4945	7415	9319	74
H(6)	4809	5729	7375	39
H(7)	4725	3662	6379	34
H(10)	2696	1887	6465	31
H(11)	-52	1252	6000	32
H(13)	-2753	-239	5823	34
H(14)	-4257	-1881	6171	35
H(15)	-2938	-2667	7150	37
H(19)	4904	-535	8868	31
H(20)	6456	889	8285	30
H(22)	1712	-63	9990	34
H(23)	537	-1159	10998	36
H(24)	70	-3277	10288	39
H(26)	61	-5222	8779	46
H(27)	494	-6333	7040	47
H(29)	1354	-6398	5203	50
H(30)	2298	-5337	4140	49
H(31)	2865	-3200	4902	44

339a

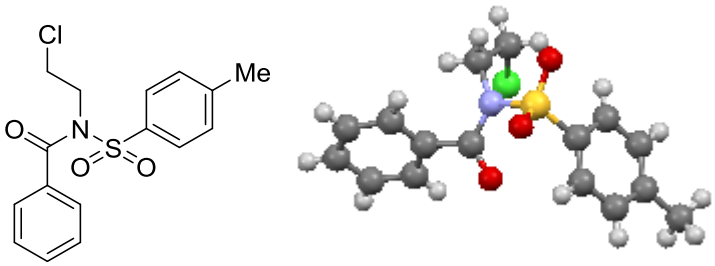


Table 1. Crystal data and structure refinement for k11cgf2.

Identification code	k11cgf2
Empirical formula	C16 H16 Cl N O3 S
Formula weight	337.81
Temperature	150(2) K
Wavelength	0.71073 A
Crystal system, space group	Monoclinic, P 1 2_1/c 1
Unit cell dimensions	a = 9.8956(2) A alpha = 90 deg. b = 12.8180(3) A beta = 90.7470(10) deg. c = 12.6466(3) A gamma = 90 deg.
Volume	1603.98(6) A^3
Z, Calculated density	4, 1.399 Mg/m^3
Absorption coefficient	0.379 mm^-1
F(000)	704
Crystal size	0.50 x 0.30 x 0.25 mm
Theta range for data collection	3.56 to 27.48 deg.
Limiting indices	-12<=h<=12, -16<=k<=16, -16<=l<=16
Reflections collected / unique	22308 / 3660 [R(int) = 0.0454]
Completeness to theta = 27.48	99.5 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9111 and 0.8330
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	3660 / 0 / 200

Goodness-of-fit on F^2	1.038
Final R indices [I>2sigma(I)]	R1 = 0.0350, wR2 = 0.0893
R indices (all data)	R1 = 0.0422, wR2 = 0.0963
Largest diff. peak and hole	0.210 and -0.426 e.A^-3

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (A^2 x 10^3) for k11cgf2.
U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

	x	y	z	U(eq)
Cl	4662(1)	3332(1)	5157(1)	57(1)
N	1795(1)	3942(1)	4191(1)	28(1)
O(1)	195(1)	3412(1)	5560(1)	34(1)
O(2)	-600(1)	3460(1)	3704(1)	39(1)
O(3)	2006(2)	3134(1)	2606(1)	47(1)
S	425(1)	3203(1)	4466(1)	27(1)
C(1)	868(1)	1885(1)	4302(1)	26(1)
C(2)	526(2)	1381(1)	3358(1)	33(1)
C(3)	848(2)	340(1)	3243(1)	36(1)
C(4)	1510(1)	-209(1)	4052(1)	33(1)
C(5)	1886(2)	-1340(1)	3900(2)	48(1)
C(6)	1832(1)	311(1)	4987(1)	31(1)
C(7)	1514(1)	1360(1)	5121(1)	28(1)
C(8)	2314(2)	3864(1)	3171(1)	31(1)
C(9)	2428(2)	4567(1)	5045(1)	31(1)
C(10)	3280(2)	3942(1)	5814(1)	39(1)
C(12)	3177(1)	4721(1)	2752(1)	28(1)
C(13)	2788(2)	5761(1)	2815(1)	35(1)
C(14)	3508(2)	6508(1)	2262(2)	49(1)
C(15)	4623(2)	6224(2)	1682(2)	53(1)
C(16)	5003(2)	5194(2)	1620(1)	50(1)
C(17)	4277(2)	4433(1)	2142(1)	38(1)

Table 3. Bond lengths [A] for k11cgf2.

Cl-C(10)	1.7886(18)
N-C(8)	1.3989(17)
N-C(9)	1.4771(17)
N-S	1.6931(12)
O(1)-S	1.4311(11)
O(2)-S	1.4279(11)
O(3)-C(8)	1.2142(18)
S-C(1)	1.7588(14)
C(1)-C(7)	1.3847(19)
C(1)-C(2)	1.3948(19)
C(2)-C(3)	1.379(2)
C(2)-H(2)	0.9500
C(3)-C(4)	1.398(2)
C(3)-H(3)	0.9500
C(4)-C(6)	1.391(2)
C(4)-C(5)	1.509(2)
C(5)-H(5A)	0.9800
C(5)-H(5B)	0.9800
C(5)-H(5C)	0.9800
C(6)-C(7)	1.392(2)
C(6)-H(6)	0.9500
C(7)-H(7)	0.9500
C(8)-C(12)	1.4924(19)
C(9)-C(10)	1.510(2)
C(9)-H(9A)	0.9900
C(9)-H(9B)	0.9900
C(10)-H(10A)	0.9900
C(10)-H(10B)	0.9900
C(12)-C(13)	1.390(2)
C(12)-C(17)	1.392(2)
C(13)-C(14)	1.389(2)
C(13)-H(13)	0.9500
C(14)-C(15)	1.382(3)
C(14)-H(14)	0.9500
C(15)-C(16)	1.375(3)
C(15)-H(15)	0.9500
C(16)-C(17)	1.385(2)
C(16)-H(16)	0.9500
C(17)-H(17)	0.9500

Table 4. Bond angles [deg] for k11cgf2.

C(8)-N-C(9)	123.76(12)
C(8)-N-S	116.98(9)
C(9)-N-S	119.11(9)
O(2)-S-O(1)	119.22(7)
O(2)-S-N	107.24(6)
O(1)-S-N	103.41(6)
O(2)-S-C(1)	108.54(7)
O(1)-S-C(1)	109.68(6)
N-S-C(1)	108.19(6)
C(7)-C(1)-C(2)	121.31(13)
C(7)-C(1)-S	119.45(11)
C(2)-C(1)-S	119.21(11)
C(3)-C(2)-C(1)	118.98(14)
C(3)-C(2)-H(2)	120.5
C(1)-C(2)-H(2)	120.5
C(2)-C(3)-C(4)	121.12(14)
C(2)-C(3)-H(3)	119.4
C(4)-C(3)-H(3)	119.4
C(6)-C(4)-C(3)	118.69(14)
C(6)-C(4)-C(5)	120.99(15)
C(3)-C(4)-C(5)	120.31(15)
C(4)-C(5)-H(5A)	109.5
C(4)-C(5)-H(5B)	109.5
H(5A)-C(5)-H(5B)	109.5
C(4)-C(5)-H(5C)	109.5
H(5A)-C(5)-H(5C)	109.5
H(5B)-C(5)-H(5C)	109.5
C(4)-C(6)-C(7)	121.19(14)
C(4)-C(6)-H(6)	119.4
C(7)-C(6)-H(6)	119.4
C(1)-C(7)-C(6)	118.71(13)
C(1)-C(7)-H(7)	120.6
C(6)-C(7)-H(7)	120.6
O(3)-C(8)-N	120.36(13)
O(3)-C(8)-C(12)	119.95(13)
N-C(8)-C(12)	119.56(12)
N-C(9)-C(10)	114.28(13)
N-C(9)-H(9A)	108.7
C(10)-C(9)-H(9A)	108.7
N-C(9)-H(9B)	108.7
C(10)-C(9)-H(9B)	108.7
H(9A)-C(9)-H(9B)	107.6
C(9)-C(10)-Cl	110.86(11)
C(9)-C(10)-H(10A)	109.5
Cl-C(10)-H(10A)	109.5
C(9)-C(10)-H(10B)	109.5
Cl-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	108.1
C(13)-C(12)-C(17)	120.36(14)
C(13)-C(12)-C(8)	121.64(13)
C(17)-C(12)-C(8)	117.17(14)
C(14)-C(13)-C(12)	119.23(16)
C(14)-C(13)-H(13)	120.4
C(12)-C(13)-H(13)	120.4
C(15)-C(14)-C(13)	120.28(17)

C(15)-C(14)-H(14)	119.9
C(13)-C(14)-H(14)	119.9
C(16)-C(15)-C(14)	120.28(16)
C(16)-C(15)-H(15)	119.9
C(14)-C(15)-H(15)	119.9
C(15)-C(16)-C(17)	120.34(17)
C(15)-C(16)-H(16)	119.8
C(17)-C(16)-H(16)	119.8
C(16)-C(17)-C(12)	119.46(16)
C(16)-C(17)-H(17)	120.3
C(12)-C(17)-H(17)	120.3

Table 5. Anisotropic displacement parameters (A^2 x 10^3) for k11cgf2. The anisotropic displacement factor exponent takes the form: -2 pi^2 [h^2 a*^2 U11 + ... + 2 h k a* b* U12]

	U11	U22	U33	U23	U13	U12
Cl	44(1)	58(1)	68(1)	-20(1)	-16(1)	11(1)
N	33(1)	29(1)	22(1)	-1(1)	1(1)	-7(1)
O(1)	39(1)	31(1)	31(1)	0(1)	10(1)	-1(1)
O(2)	36(1)	36(1)	44(1)	7(1)	-10(1)	-1(1)
O(3)	78(1)	40(1)	24(1)	-4(1)	8(1)	-24(1)
S	29(1)	26(1)	26(1)	2(1)	0(1)	-1(1)
C(1)	26(1)	28(1)	24(1)	1(1)	2(1)	-4(1)
C(2)	37(1)	35(1)	26(1)	0(1)	-2(1)	-9(1)
C(3)	39(1)	37(1)	31(1)	-8(1)	5(1)	-12(1)
C(4)	28(1)	28(1)	43(1)	-4(1)	12(1)	-6(1)
C(5)	45(1)	31(1)	68(1)	-11(1)	17(1)	-3(1)
C(6)	29(1)	31(1)	34(1)	3(1)	4(1)	1(1)
C(7)	30(1)	31(1)	24(1)	-1(1)	2(1)	-1(1)
C(8)	39(1)	31(1)	23(1)	1(1)	1(1)	-5(1)
C(9)	39(1)	29(1)	26(1)	-5(1)	0(1)	-5(1)
C(10)	46(1)	40(1)	32(1)	-7(1)	-9(1)	-3(1)
C(12)	30(1)	30(1)	25(1)	3(1)	-1(1)	-3(1)
C(13)	42(1)	32(1)	31(1)	1(1)	1(1)	-1(1)
C(14)	73(1)	32(1)	42(1)	6(1)	-3(1)	-12(1)
C(15)	54(1)	62(1)	44(1)	17(1)	-1(1)	-29(1)
C(16)	30(1)	77(1)	42(1)	15(1)	6(1)	-4(1)
C(17)	33(1)	46(1)	36(1)	8(1)	3(1)	8(1)

Table 6. Hydrogen coordinates (x 10^4) and isotropic displacement parameters (A^2 x 10^3) for k11cgf2.

	x	y	z	U(eq)
H(2)	77	1748	2804	39
H(3)	616	-9	2604	43
H(5A)	2658	-1387	3426	72
H(5B)	1115	-1717	3590	72
H(5C)	2127	-1649	4586	72
H(6)	2276	-56	5543	38
H(7)	1736	1710	5763	34
H(9A)	1707	4926	5441	37
H(9B)	3002	5110	4722	37
H(10A)	2714	3401	6149	47
H(10B)	3633	4407	6379	47
H(13)	2037	5958	3231	42
H(14)	3234	7218	2283	59
H(15)	5129	6742	1324	64
H(16)	5768	5004	1217	59
H(17)	4527	3720	2084	46

339c

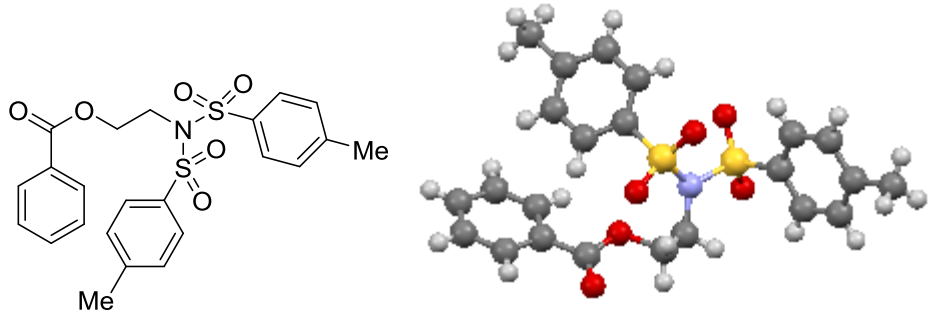


Table 1. Crystal data and structure refinement for h11cgf3.

Identification code	h11cgf3
Empirical formula	C23 H23 N O6 S2
Formula weight	473.54
Temperature	150(2) K
Wavelength	0.71073 A
Crystal system, space group	Triclinic, P $\bar{1}$
Unit cell dimensions	a = 8.3900(4) A alpha = 96.182(3) deg. b = 9.7467(5) A beta = 90.136(2) deg. c = 14.8460(8) A gamma = 115.476(7) deg.
Volume	1088.00(10) A^3
Z, Calculated density	2, 1.445 Mg/m^3
Absorption coefficient	0.286 mm^-1
F(000)	496
Crystal size	0.50 x 0.20 x 0.15 mm
Theta range for data collection	4.15 to 27.56 deg.
Limiting indices	-10<=h<=10, -12<=k<=12, -19<=l<=19
Reflections collected / unique	19447 / 4852 [R(int) = 0.0913]
Completeness to theta = 27.56	96.7 %
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9583 and 0.8701
Refinement method	Full-matrix least-squares on F^2

Data / restraints / parameters	4852 / 0 / 291
Goodness-of-fit on F^2	1.011
Final R indices [I>2sigma(I)]	R1 = 0.0512, wR2 = 0.1036
R indices (all data)	R1 = 0.1201, wR2 = 0.1253
Largest diff. peak and hole	0.305 and -0.521 e.A^-3

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (A^2 x 10^3) for h11cgf3.
U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

	x	y	z	U(eq)
S(1)	6116(1)	-138(1)	-7996(1)	26(1)
S(2)	2369(1)	-1874(1)	-7685(1)	27(1)
O(1)	5588(3)	-1012(2)	-8867(1)	31(1)
O(2)	7716(2)	84(2)	-7532(1)	32(1)
O(3)	2158(2)	-979(2)	-8331(1)	34(1)
O(4)	1381(2)	-2091(2)	-6883(1)	36(1)
O(5)	4850(2)	-3166(2)	-6042(1)	29(1)
O(6)	3272(3)	-2971(2)	-4848(1)	35(1)
C(1)	6415(4)	6128(3)	-8213(2)	41(1)
C(2)	6342(4)	4567(3)	-8157(2)	30(1)
C(3)	5419(4)	3357(3)	-8831(2)	32(1)
C(4)	5324(4)	1910(3)	-8783(2)	30(1)
C(5)	6165(3)	1669(3)	-8056(2)	26(1)
C(6)	7097(4)	2861(3)	-7376(2)	29(1)
C(7)	7172(4)	4291(3)	-7441(2)	30(1)
C(8)	1981(3)	-3687(3)	-8234(2)	25(1)
C(9)	2069(4)	-3904(3)	-9170(2)	33(1)
C(10)	1657(4)	-5361(3)	-9591(2)	37(1)
C(11)	1172(4)	-6595(3)	-9100(2)	35(1)
C(12)	675(4)	-8195(3)	-9564(2)	50(1)
C(13)	1120(4)	-6344(3)	-8168(2)	35(1)
C(14)	1503(4)	-4907(3)	-7730(2)	31(1)
N	4518(3)	-1044(2)	-7297(1)	25(1)
C(15)	4950(4)	-671(3)	-6303(2)	30(1)
C(16)	5893(4)	-1526(3)	-5933(2)	32(1)
C(17)	3627(4)	-3744(3)	-5428(2)	27(1)
C(18)	2757(3)	-5456(3)	-5575(2)	26(1)
C(19)	3388(4)	-6276(3)	-6176(2)	33(1)
C(20)	2501(4)	-7853(3)	-6329(2)	36(1)
C(21)	978(4)	-8624(3)	-5887(2)	38(1)
C(22)	356(4)	-7816(3)	-5277(2)	38(1)
C(23)	1244(4)	-6238(3)	-5120(2)	32(1)

Table 3. Bond lengths [A] for h11cgf3.

S(1)-O(1)	1.4248(18)
S(1)-O(2)	1.4270(19)
S(1)-N	1.685(2)
S(1)-C(5)	1.756(3)
S(2)-O(3)	1.4231(19)
S(2)-O(4)	1.434(2)
S(2)-N	1.696(2)
S(2)-C(8)	1.756(2)
O(5)-C(17)	1.349(3)
O(5)-C(16)	1.445(3)
O(6)-C(17)	1.205(3)
C(1)-C(2)	1.507(3)
C(1)-H(1A)	0.9800
C(1)-H(1B)	0.9800
C(1)-H(1C)	0.9800
C(2)-C(7)	1.381(4)
C(2)-C(3)	1.395(4)
C(3)-C(4)	1.388(4)
C(3)-H(3)	0.9500
C(4)-C(5)	1.383(4)
C(4)-H(4)	0.9500
C(5)-C(6)	1.394(4)
C(6)-C(7)	1.381(4)
C(6)-H(6)	0.9500
C(7)-H(7)	0.9500
C(8)-C(14)	1.385(4)
C(8)-C(9)	1.390(4)
C(9)-C(10)	1.383(4)
C(9)-H(9)	0.9500
C(10)-C(11)	1.383(4)
C(10)-H(10)	0.9500
C(11)-C(13)	1.383(4)
C(11)-C(12)	1.512(4)
C(12)-H(12A)	0.9800
C(12)-H(12B)	0.9800
C(12)-H(12C)	0.9800
C(13)-C(14)	1.380(4)
C(13)-H(13)	0.9500
C(14)-H(14)	0.9500
N-C(15)	1.487(3)
C(15)-C(16)	1.511(4)
C(15)-H(15A)	0.9900
C(15)-H(15B)	0.9900
C(16)-H(16A)	0.9900
C(16)-H(16B)	0.9900
C(17)-C(18)	1.496(4)
C(18)-C(19)	1.388(4)
C(18)-C(23)	1.389(4)
C(19)-C(20)	1.381(4)
C(19)-H(19)	0.9500
C(20)-C(21)	1.383(4)
C(20)-H(20)	0.9500
C(21)-C(22)	1.384(4)
C(21)-H(21)	0.9500
C(22)-C(23)	1.382(4)

Table 4. Bond lengths [A] and angles [deg] for h11cgf3.

O(1)-S(1)-O(2)	120.72(12)
O(1)-S(1)-N	106.57(10)
O(2)-S(1)-N	104.49(11)
O(1)-S(1)-C(5)	109.05(12)
O(2)-S(1)-C(5)	107.99(12)
N-S(1)-C(5)	107.23(12)
O(3)-S(2)-O(4)	119.95(12)
O(3)-S(2)-N	108.01(11)
O(4)-S(2)-N	104.84(11)
O(3)-S(2)-C(8)	109.19(12)
O(4)-S(2)-C(8)	108.02(12)
N-S(2)-C(8)	105.94(12)
C(17)-O(5)-C(16)	116.9(2)
C(2)-C(1)-H(1A)	109.5
C(2)-C(1)-H(1B)	109.5
H(1A)-C(1)-H(1B)	109.5
C(2)-C(1)-H(1C)	109.5
H(1A)-C(1)-H(1C)	109.5
H(1B)-C(1)-H(1C)	109.5
C(7)-C(2)-C(3)	118.3(2)
C(7)-C(2)-C(1)	121.3(2)
C(3)-C(2)-C(1)	120.5(3)
C(4)-C(3)-C(2)	121.1(3)
C(4)-C(3)-H(3)	119.5
C(2)-C(3)-H(3)	119.5
C(5)-C(4)-C(3)	119.2(3)
C(5)-C(4)-H(4)	120.4
C(3)-C(4)-H(4)	120.4
C(4)-C(5)-C(6)	120.6(2)
C(4)-C(5)-S(1)	120.1(2)
C(6)-C(5)-S(1)	119.3(2)
C(7)-C(6)-C(5)	118.9(3)
C(7)-C(6)-H(6)	120.5
C(5)-C(6)-H(6)	120.5
C(2)-C(7)-C(6)	121.9(2)
C(2)-C(7)-H(7)	119.1
C(6)-C(7)-H(7)	119.1
C(14)-C(8)-C(9)	120.5(2)
C(14)-C(8)-S(2)	119.2(2)
C(9)-C(8)-S(2)	120.1(2)
C(10)-C(9)-C(8)	119.0(3)
C(10)-C(9)-H(9)	120.5
C(8)-C(9)-H(9)	120.5
C(11)-C(10)-C(9)	121.4(3)
C(11)-C(10)-H(10)	119.3
C(9)-C(10)-H(10)	119.3
C(10)-C(11)-C(13)	118.5(3)
C(10)-C(11)-C(12)	121.4(3)
C(13)-C(11)-C(12)	120.1(3)
C(11)-C(12)-H(12A)	109.5
C(11)-C(12)-H(12B)	109.5
H(12A)-C(12)-H(12B)	109.5
C(11)-C(12)-H(12C)	109.5
H(12A)-C(12)-H(12C)	109.5
H(12B)-C(12)-H(12C)	109.5

C(14)-C(13)-C(11)	121.4(3)
C(14)-C(13)-H(13)	119.3
C(11)-C(13)-H(13)	119.3
C(13)-C(14)-C(8)	119.2(3)
C(13)-C(14)-H(14)	120.4
C(8)-C(14)-H(14)	120.4
C(15)-N-S(1)	117.95(17)
C(15)-N-S(2)	119.22(18)
S(1)-N-S(2)	119.85(13)
N-C(15)-C(16)	113.8(2)
N-C(15)-H(15A)	108.8
C(16)-C(15)-H(15A)	108.8
N-C(15)-H(15B)	108.8
C(16)-C(15)-H(15B)	108.8
H(15A)-C(15)-H(15B)	107.7
O(5)-C(16)-C(15)	113.3(2)
O(5)-C(16)-H(16A)	108.9
C(15)-C(16)-H(16A)	108.9
O(5)-C(16)-H(16B)	108.9
C(15)-C(16)-H(16B)	108.9
H(16A)-C(16)-H(16B)	107.7
O(6)-C(17)-O(5)	124.0(2)
O(6)-C(17)-C(18)	124.9(3)
O(5)-C(17)-C(18)	111.1(2)
C(19)-C(18)-C(23)	119.4(2)
C(19)-C(18)-C(17)	121.7(3)
C(23)-C(18)-C(17)	118.9(2)
C(20)-C(19)-C(18)	120.2(3)
C(20)-C(19)-H(19)	119.9
C(18)-C(19)-H(19)	119.9
C(19)-C(20)-C(21)	120.2(3)
C(19)-C(20)-H(20)	119.9
C(21)-C(20)-H(20)	119.9
C(20)-C(21)-C(22)	119.9(3)
C(20)-C(21)-H(21)	120.0
C(22)-C(21)-H(21)	120.0
C(23)-C(22)-C(21)	119.9(3)
C(23)-C(22)-H(22)	120.0
C(21)-C(22)-H(22)	120.0
C(22)-C(23)-C(18)	120.4(3)
C(22)-C(23)-H(23)	119.8
C(18)-C(23)-H(23)	119.8

Table 5. Anisotropic displacement parameters (A^2 x 10^3) for h11cgf3. The anisotropic displacement factor exponent takes the form: -2 pi^2 [h^2 a*^2 U11 + ... + 2 h k a* b* U12]

	U11	U22	U33	U23	U13	U12
S(1)	29(1)	21(1)	29(1)	3(1)	4(1)	11(1)
S(2)	27(1)	23(1)	32(1)	1(1)	2(1)	10(1)
O(1)	43(1)	23(1)	27(1)	1(1)	6(1)	13(1)
O(2)	27(1)	26(1)	41(1)	7(1)	1(1)	11(1)
O(3)	37(1)	29(1)	39(1)	4(1)	-4(1)	18(1)
O(4)	31(1)	37(1)	34(1)	-2(1)	9(1)	11(1)
O(5)	32(1)	24(1)	30(1)	8(1)	7(1)	8(1)
O(6)	44(1)	29(1)	30(1)	0(1)	8(1)	14(1)
C(1)	53(2)	27(2)	49(2)	8(1)	14(2)	24(1)
C(2)	29(2)	25(1)	38(2)	8(1)	14(1)	13(1)
C(3)	37(2)	30(2)	35(2)	10(1)	3(1)	18(1)
C(4)	33(2)	26(1)	28(2)	4(1)	1(1)	10(1)
C(5)	28(2)	21(1)	31(2)	9(1)	8(1)	10(1)
C(6)	32(2)	23(1)	29(2)	5(1)	0(1)	8(1)
C(7)	34(2)	20(1)	32(2)	-1(1)	6(1)	8(1)
C(8)	24(2)	20(1)	27(2)	-1(1)	-1(1)	7(1)
C(9)	35(2)	25(2)	32(2)	5(1)	6(1)	7(1)
C(10)	39(2)	32(2)	34(2)	-6(1)	3(1)	10(1)
C(11)	28(2)	26(2)	47(2)	-3(1)	-2(2)	10(1)
C(12)	50(2)	27(2)	64(2)	-10(2)	-3(2)	12(2)
C(13)	32(2)	21(2)	46(2)	7(1)	-4(2)	6(1)
C(14)	31(2)	27(2)	32(2)	1(1)	-2(1)	9(1)
N	26(1)	19(1)	26(1)	2(1)	2(1)	7(1)
C(15)	37(2)	19(1)	26(2)	0(1)	2(1)	6(1)
C(16)	31(2)	24(2)	33(2)	8(1)	-1(1)	4(1)
C(17)	28(2)	31(2)	24(2)	9(1)	1(1)	13(1)
C(18)	27(2)	25(1)	26(2)	8(1)	0(1)	11(1)
C(19)	35(2)	29(2)	36(2)	10(1)	9(1)	14(1)
C(20)	44(2)	30(2)	35(2)	3(1)	1(2)	19(1)
C(21)	34(2)	26(2)	47(2)	9(1)	-6(2)	6(1)
C(22)	30(2)	33(2)	52(2)	17(2)	9(2)	10(1)
C(23)	32(2)	34(2)	35(2)	9(1)	7(1)	16(1)

Table 6. Hydrogen coordinates (x 10^4) and isotropic displacement parameters (A^2 x 10^3) for h11cgf3.

	x	y	z	U(eq)
H(1A)	5637	6310	-7773	61
H(1B)	6025	6178	-8826	61
H(1C)	7631	6910	-8076	61
H(3)	4846	3528	-9331	38
H(4)	4690	1094	-9245	36
H(6)	7670	2694	-6875	35
H(7)	7814	5107	-6981	36
H(9)	2408	-3065	-9514	39
H(10)	1708	-5517	-10231	45
H(12A)	770	-8835	-9121	74
H(12B)	1477	-8153	-10050	74
H(12C)	-543	-8632	-9822	74
H(13)	814	-7179	-7823	42
H(14)	1439	-4756	-7090	38
H(15A)	3841	-910	-5987	36
H(15B)	5703	443	-6166	36
H(16A)	7005	-1284	-6247	38
H(16B)	6209	-1162	-5280	38
H(19)	4432	-5751	-6482	39
H(20)	2939	-8409	-6740	43
H(21)	360	-9707	-6002	45
H(22)	-680	-8345	-4965	46
H(23)	817	-5686	-4700	39

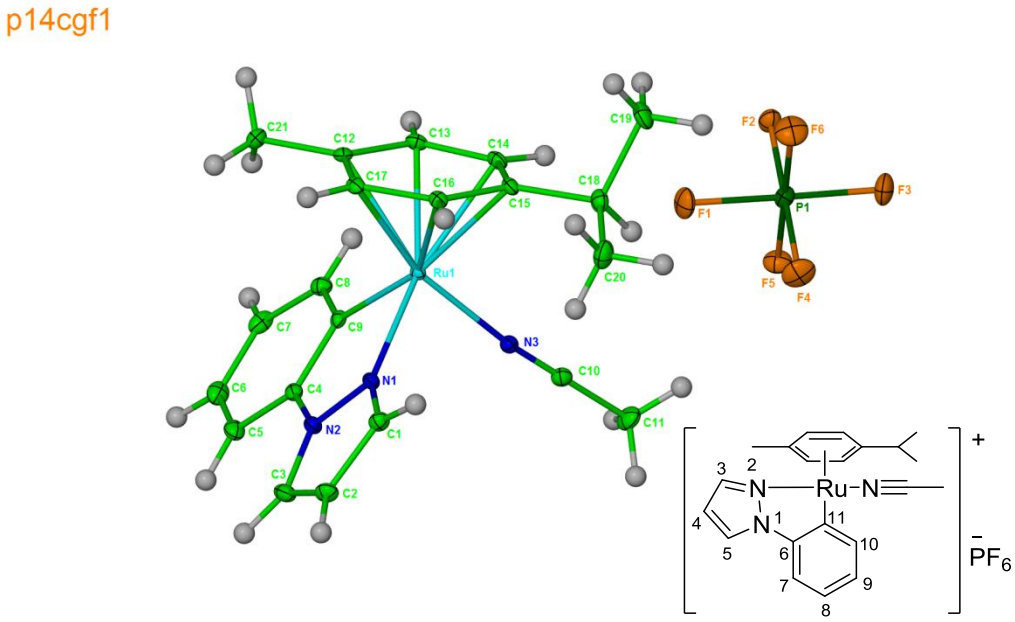


Table 1. Crystal data and structure refinement for 1.

Identification code	p14cgf1
Empirical formula	C21 H24 F6 N3 P Ru
Formula weight	564.47
Temperature	150(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	P21/n
Unit cell dimensions	a = 8.8084(2)Å alpha = 90°
	b = 10.2005(2)Å beta = 91.799(2)°
	c = 24.4182(6)Å gamma = 90°
Volume	2192.90(9) $Å^3$
Z	4
Density (calculated)	1.710 Mg/m^3
Absorption coefficient	0.853 mm^{-1}
F(000)	1136
Crystal size	0.40 x 0.15 x 0.06 mm
Theta range for data collection	3.52 to 27.48 °.
Index ranges	-11<=h<=10; -13<=k<=13; -31<=l<=25
Reflections collected	17013
Independent reflections	5026 [R(int) = 0.0367]
Reflections observed (>2sigma)	4338
Data Completeness	0.997
Absorption correction	Analytical
Max. and min. transmission	0.974 and 0.881
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	5026 / 0 / 293
Goodness-of-fit on F^2	1.082
Final R indices [I>2sigma(I)]	*R*1 = 0.0318 *wR*2 = 0.0624

R indices (all data)	$R1$ = 0.0410 $wR2$ = 0.0655
Largest diff. peak and hole	0.596 and -0.532 eÅ^{-3}

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) for 1.U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

Atom	x	y	z	U(eq)
Ru(1)	4608(1)	4549(1)	1607(1)	14(1)
P(1)	7234(1)	9798(1)	811(1)	22(1)
F(1)	6634(2)	8548(2)	1137(1)	38(1)
N(1)	3030(2)	3346(2)	1205(1)	17(1)
C(1)	2951(3)	2603(2)	756(1)	21(1)
F(2)	7889(2)	10406(2)	1378(1)	30(1)
N(2)	1690(2)	3178(2)	1459(1)	19(1)
C(2)	1556(3)	1965(3)	714(1)	25(1)
F(3)	7843(2)	11061(2)	496(1)	40(1)
N(3)	3638(2)	6144(2)	1217(1)	19(1)
C(3)	781(3)	2336(3)	1165(1)	26(1)
F(4)	6568(2)	9203(2)	252(1)	44(1)
C(4)	1535(3)	3877(2)	1956(1)	18(1)
F(5)	5662(2)	10535(2)	909(1)	34(1)
C(5)	236(3)	3764(3)	2260(1)	26(1)
F(6)	8807(2)	9081(2)	723(1)	45(1)
C(6)	185(3)	4445(3)	2744(1)	29(1)
C(7)	1371(3)	5233(3)	2912(1)	26(1)
C(8)	2648(3)	5351(3)	2596(1)	22(1)
C(9)	2780(3)	4648(2)	2112(1)	17(1)
C(10)	3192(3)	7101(3)	1035(1)	22(1)
C(11)	2630(3)	8333(3)	804(1)	32(1)
C(12)	6020(3)	3741(2)	2289(1)	18(1)
C(13)	6308(3)	5114(2)	2233(1)	20(1)
C(14)	6723(3)	5632(2)	1726(1)	21(1)
C(15)	6980(3)	4821(2)	1259(1)	17(1)
C(16)	6675(3)	3483(2)	1312(1)	18(1)
C(17)	6175(3)	2958(2)	1819(1)	18(1)
C(18)	7501(3)	5436(3)	732(1)	24(1)
C(19)	9181(3)	5807(3)	795(1)	34(1)
C(20)	7230(4)	4576(3)	232(1)	35(1)
C(21)	5524(3)	3171(3)	2819(1)	24(1)

Table 3. Bond lengths [Å] and angles [°] for 1.

Ru(1)-N(3)	2.058(2)	Ru(1)-C(9)	2.060(2)
Ru(1)-N(1)	2.078(2)	Ru(1)-C(14)	2.178(2)
Ru(1)-C(13)	2.182(2)	Ru(1)-C(17)	2.182(2)
Ru(1)-C(12)	2.206(2)	Ru(1)-C(16)	2.258(2)
Ru(1)-C(15)	2.298(2)	P(1)-F(6)	1.5870(18)
P(1)-F(4)	1.5877(18)	P(1)-F(5)	1.6002(17)
P(1)-F(3)	1.6010(17)	P(1)-F(1)	1.6029(17)
P(1)-F(2)	1.6085(16)	N(1)-C(1)	1.332(3)
N(1)-N(2)	1.361(3)	C(1)-C(2)	1.392(4)
C(1)-H(1)	0.9500	N(2)-C(3)	1.362(3)
N(2)-C(4)	1.420(3)	C(2)-C(3)	1.368(4)
C(2)-H(2)	0.9500	N(3)-C(10)	1.137(3)
C(3)-H(3)	0.9500	C(4)-C(5)	1.387(3)
C(4)-C(9)	1.393(3)	C(5)-C(6)	1.374(4)
C(5)-H(5)	0.9500	C(6)-C(7)	1.371(4)
C(6)-H(6)	0.9500	C(7)-C(8)	1.389(4)
C(7)-H(7)	0.9500	C(8)-C(9)	1.389(3)
C(8)-H(8)	0.9500	C(10)-C(11)	1.457(4)
C(11)-H(11A)	0.9800	C(11)-H(11B)	0.9800
C(11)-H(11C)	0.9800	C(12)-C(17)	1.407(4)
C(12)-C(13)	1.430(3)	C(12)-C(21)	1.497(3)
C(13)-C(14)	1.403(4)	C(13)-H(13)	0.9500
C(14)-C(15)	1.434(3)	C(14)-H(14)	0.9500
C(15)-C(16)	1.398(3)	C(15)-C(18)	1.515(3)
C(16)-C(17)	1.431(3)	C(16)-H(16)	0.9500
C(17)-H(17)	0.9500	C(18)-C(20)	1.516(4)
C(18)-C(19)	1.530(4)	C(18)-H(18)	1.0000
C(19)-H(19A)	0.9800	C(19)-H(19B)	0.9800
C(19)-H(19C)	0.9800	C(20)-H(20A)	0.9800
C(20)-H(20B)	0.9800	C(20)-H(20C)	0.9800
C(21)-H(21A)	0.9800	C(21)-H(21B)	0.9800
C(21)-H(21C)	0.9800		

N(3)-Ru(1)-C(9)	85.24(9)	N(3)-Ru(1)-N(1)	89.20(8)
C(9)-Ru(1)-N(1)	77.77(9)	N(3)-Ru(1)-C(14)	90.09(9)
C(9)-Ru(1)-C(14)	125.21(10)	N(1)-Ru(1)-C(14)	156.85(9)
N(3)-Ru(1)-C(13)	112.39(9)	C(9)-Ru(1)-C(13)	95.80(9)
N(1)-Ru(1)-C(13)	157.08(9)	C(14)-Ru(1)-C(13)	37.54(9)
N(3)-Ru(1)-C(17)	161.46(9)	C(9)-Ru(1)-C(17)	113.30(9)
N(1)-Ru(1)-C(17)	94.71(8)	C(14)-Ru(1)-C(17)	79.24(9)
C(13)-Ru(1)-C(17)	67.37(9)	N(3)-Ru(1)-C(12)	149.41(9)
C(9)-Ru(1)-C(12)	90.03(9)	N(1)-Ru(1)-C(12)	119.31(9)
C(14)-Ru(1)-C(12)	68.21(9)	C(13)-Ru(1)-C(12)	38.04(9)
C(17)-Ru(1)-C(12)	37.41(9)	N(3)-Ru(1)-C(16)	124.06(8)
C(9)-Ru(1)-C(16)	150.19(9)	N(1)-Ru(1)-C(16)	95.67(8)
C(14)-Ru(1)-C(16)	65.91(9)	C(13)-Ru(1)-C(16)	78.92(9)
C(17)-Ru(1)-C(16)	37.55(9)	C(12)-Ru(1)-C(16)	67.63(9)
N(3)-Ru(1)-C(15)	95.84(8)	C(9)-Ru(1)-C(15)	162.27(9)
N(1)-Ru(1)-C(15)	119.90(8)	C(14)-Ru(1)-C(15)	37.26(9)
C(13)-Ru(1)-C(15)	67.38(9)	C(17)-Ru(1)-C(15)	66.54(9)
C(12)-Ru(1)-C(15)	80.03(9)	C(16)-Ru(1)-C(15)	35.72(8)
F(6)-P(1)-F(4)	90.51(10)	F(6)-P(1)-F(5)	178.89(11)

F(4)-P(1)-F(5)	90.60(10)	F(6)-P(1)-F(3)	89.99(10)
F(4)-P(1)-F(3)	90.93(10)	F(5)-P(1)-F(3)	89.93(9)
F(6)-P(1)-F(1)	90.16(10)	F(4)-P(1)-F(1)	90.23(10)
F(5)-P(1)-F(1)	89.90(9)	F(3)-P(1)-F(1)	178.83(10)
F(6)-P(1)-F(2)	90.13(10)	F(4)-P(1)-F(2)	179.33(10)
F(5)-P(1)-F(2)	88.76(9)	F(3)-P(1)-F(2)	89.25(9)
F(1)-P(1)-F(2)	89.58(9)	C(1)-N(1)-N(2)	106.3(2)
C(1)-N(1)-Ru(1)	137.85(17)	N(2)-N(1)-Ru(1)	115.82(15)
N(1)-C(1)-C(2)	110.4(2)	N(1)-C(1)-H(1)	124.8
C(2)-C(1)-H(1)	124.8	N(1)-N(2)-C(3)	110.1(2)
N(1)-N(2)-C(4)	115.78(19)	C(3)-N(2)-C(4)	134.1(2)
C(3)-C(2)-C(1)	105.8(2)	C(3)-C(2)-H(2)	127.1
C(1)-C(2)-H(2)	127.1	C(10)-N(3)-Ru(1)	173.2(2)
N(2)-C(3)-C(2)	107.4(2)	N(2)-C(3)-H(3)	126.3
C(2)-C(3)-H(3)	126.3	C(5)-C(4)-C(9)	123.8(2)
C(5)-C(4)-N(2)	121.3(2)	C(9)-C(4)-N(2)	114.9(2)
C(6)-C(5)-C(4)	117.9(3)	C(6)-C(5)-H(5)	121.0
C(4)-C(5)-H(5)	121.0	C(7)-C(6)-C(5)	120.5(3)
C(7)-C(6)-H(6)	119.8	C(5)-C(6)-H(6)	119.8
C(6)-C(7)-C(8)	120.6(2)	C(6)-C(7)-H(7)	119.7
C(8)-C(7)-H(7)	119.7	C(7)-C(8)-C(9)	121.2(2)
C(7)-C(8)-H(8)	119.4	C(9)-C(8)-H(8)	119.4
C(8)-C(9)-C(4)	115.9(2)	C(8)-C(9)-Ru(1)	128.41(19)
C(4)-C(9)-Ru(1)	115.65(18)	N(3)-C(10)-C(11)	179.5(3)
C(10)-C(11)-H(11A)	109.5	C(10)-C(11)-H(11B)	109.5
H(11A)-C(11)-H(11B)	109.5	C(10)-C(11)-H(11C)	109.5
H(11A)-C(11)-H(11C)	109.5	H(11B)-C(11)-H(11C)	109.5
C(17)-C(12)-C(13)	117.1(2)	C(17)-C(12)-C(21)	121.5(2)
C(13)-C(12)-C(21)	121.4(2)	C(17)-C(12)-Ru(1)	70.39(14)
C(13)-C(12)-Ru(1)	70.08(14)	C(21)-C(12)-Ru(1)	128.64(17)
C(14)-C(13)-C(12)	120.4(2)	C(14)-C(13)-Ru(1)	71.06(14)
C(12)-C(13)-Ru(1)	71.88(14)	C(14)-C(13)-H(13)	119.8
C(12)-C(13)-H(13)	119.8	Ru(1)-C(13)-H(13)	129.7
C(13)-C(14)-C(15)	122.4(2)	C(13)-C(14)-Ru(1)	71.39(14)
C(15)-C(14)-Ru(1)	75.92(14)	C(13)-C(14)-H(14)	118.8
C(15)-C(14)-H(14)	118.8	Ru(1)-C(14)-H(14)	125.7
C(16)-C(15)-C(14)	116.9(2)	C(16)-C(15)-C(18)	123.3(2)
C(14)-C(15)-C(18)	119.8(2)	C(16)-C(15)-Ru(1)	70.57(13)
C(14)-C(15)-Ru(1)	66.82(13)	C(18)-C(15)-Ru(1)	131.93(17)
C(15)-C(16)-C(17)	120.8(2)	C(15)-C(16)-Ru(1)	73.71(14)
C(17)-C(16)-Ru(1)	68.36(13)	C(15)-C(16)-H(16)	119.6
C(17)-C(16)-H(16)	119.6	Ru(1)-C(16)-H(16)	131.1
C(12)-C(17)-C(16)	122.2(2)	C(12)-C(17)-Ru(1)	72.21(14)
C(16)-C(17)-Ru(1)	74.09(14)	C(12)-C(17)-H(17)	118.9
C(16)-C(17)-H(17)	118.9	Ru(1)-C(17)-H(17)	126.8
C(15)-C(18)-C(20)	113.6(2)	C(15)-C(18)-C(19)	109.6(2)
C(20)-C(18)-C(19)	110.6(2)	C(15)-C(18)-H(18)	107.6
C(20)-C(18)-H(18)	107.6	C(19)-C(18)-H(18)	107.6
C(18)-C(19)-H(19A)	109.5	C(18)-C(19)-H(19B)	109.5
H(19A)-C(19)-H(19B)	109.5	C(18)-C(19)-H(19C)	109.5
H(19A)-C(19)-H(19C)	109.5	H(19B)-C(19)-H(19C)	109.5
C(18)-C(20)-H(20A)	109.5	C(18)-C(20)-H(20B)	109.5
H(20A)-C(20)-H(20B)	109.5	C(18)-C(20)-H(20C)	109.5
H(20A)-C(20)-H(20C)	109.5	H(20B)-C(20)-H(20C)	109.5
C(12)-C(21)-H(21A)	109.5	C(12)-C(21)-H(21B)	109.5
H(21A)-C(21)-H(21B)	109.5	C(12)-C(21)-H(21C)	109.5

H(21A)-C(21)-H(21C) 109.5 H(21B)-C(21)-H(21C) 109.5

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2$ x 10^3) for 1. The anisotropic displacement factor exponent takes the form: -2 gpi^2 [h^2 a^{*2} U11 + ... + 2 h k a* b* U

Atom	U11	U22	U33	U23	U13	U12
Ru(1)	13(1)	12(1)	17(1)	0(1)	-0(1)	-1(1)
P(1)	28(1)	18(1)	20(1)	-1(1)	2(1)	4(1)
F(1)	55(1)	17(1)	42(1)	4(1)	3(1)	-6(1)
N(1)	14(1)	16(1)	21(1)	1(1)	1(1)	-1(1)
C(1)	24(1)	21(1)	19(1)	-2(1)	-1(1)	1(1)
F(2)	37(1)	28(1)	24(1)	-1(1)	-4(1)	-4(1)
N(2)	14(1)	19(1)	23(1)	2(1)	0(1)	-1(1)
C(2)	28(1)	21(1)	24(1)	-6(1)	-7(1)	-3(1)
F(3)	54(1)	34(1)	31(1)	10(1)	11(1)	-4(1)
N(3)	18(1)	18(1)	21(1)	1(1)	-2(1)	-2(1)
C(3)	19(1)	22(1)	36(2)	2(1)	-6(1)	-3(1)
F(4)	59(1)	44(1)	29(1)	-17(1)	-7(1)	6(1)
C(4)	16(1)	17(1)	22(1)	5(1)	-0(1)	2(1)
F(5)	29(1)	30(1)	42(1)	-6(1)	-2(1)	10(1)
C(5)	17(1)	27(1)	33(2)	4(1)	2(1)	1(1)
F(6)	38(1)	45(1)	54(1)	-7(1)	9(1)	18(1)
C(6)	24(1)	33(2)	29(2)	5(1)	8(1)	6(1)
C(7)	29(1)	30(2)	19(1)	-2(1)	3(1)	14(1)
C(8)	22(1)	20(1)	25(1)	-1(1)	-3(1)	3(1)
C(9)	17(1)	16(1)	18(1)	4(1)	1(1)	4(1)
C(10)	22(1)	23(1)	20(1)	-2(1)	-2(1)	-1(1)
C(11)	39(2)	21(1)	36(2)	6(1)	-9(1)	5(1)
C(12)	12(1)	22(1)	20(1)	2(1)	-4(1)	1(1)
C(13)	16(1)	22(1)	22(1)	-6(1)	-2(1)	-2(1)
C(14)	16(1)	14(1)	32(2)	-2(1)	-1(1)	-3(1)
C(15)	12(1)	16(1)	23(1)	1(1)	2(1)	-1(1)
C(16)	15(1)	15(1)	23(1)	-2(1)	1(1)	2(1)
C(17)	14(1)	14(1)	27(1)	2(1)	-2(1)	2(1)
C(18)	25(1)	17(1)	29(1)	4(1)	5(1)	1(1)
C(19)	27(2)	33(2)	42(2)	5(1)	12(1)	-7(1)
C(20)	49(2)	32(2)	24(2)	6(1)	4(1)	-5(2)
C(21)	26(1)	27(1)	20(1)	4(1)	-2(1)	1(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

Atom	x	y	z	U(eq)
H(1)	3737	2521	500	25
H(2)	1213	1390	430	30
H(3)	-208	2057	1257	31
H(5)	-592	3232	2137	31
H(6)	-680	4369	2965	34
H(7)	1320	5702	3247	31
H(8)	3446	5922	2712	27
H(11A)	2249	8885	1098	48
H(11B)	1805	8154	536	48
H(11C)	3457	8788	624	48
H(13)	6217	5678	2539	24
H(14)	6838	6554	1693	25
H(16)	6800	2916	1009	21
H(17)	5941	2051	1840	22
H(18)	6911	6264	672	28
H(19A)	9330	6385	1112	51
H(19B)	9497	6261	463	51
H(19C)	9791	5011	848	51
H(20A)	7835	3774	271	52
H(20B)	7530	5051	-96	52
H(20C)	6150	4349	198	52
H(21A)	5116	2289	2754	37
H(21B)	4737	3729	2972	37
H(21C)	6396	3122	3078	37

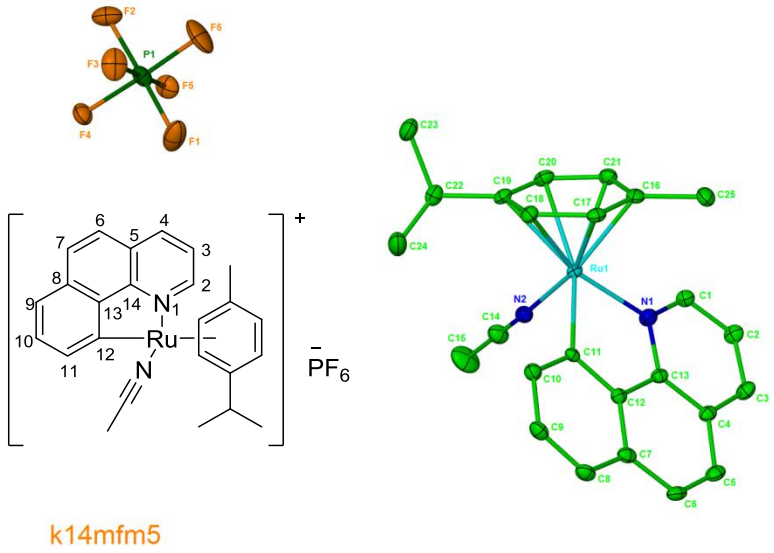


Table 1. Crystal data and structure refinement for 1.

Identification code	k14mfm5
Empirical formula	C25 H25 F6 N2 P Ru U0
Formula weight	599.51
Temperature	150(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	C2
Unit cell dimensions	a = 25.0510(5)Å alpha = 90°
	b = 10.4130(2)Å beta = 106.547(1)°
	c = 9.9960(2)Å gamma = 90°
Volume	2499.53(9) Å^3
Z	4
Density (calculated)	1.593 Mg/m^3
Absorption coefficient	0.752 mm^{-1}
F(000)	1208
Crystal size	0.25 x 0.15 x 0.08 mm
Theta range for data collection	3.91 to 27.47 °.
Index ranges	-32<=h<=32; -13<=k<=12; -12<=l<=12
Reflections collected	18031
Independent reflections	5494 [R(int) = 0.0405]
Reflections observed (>2sigma)	5214
Data Completeness	0.993
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.90 and 0.61
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	5494 / 1 / 320
Goodness-of-fit on F^2	1.070
Final R indices [I>2sigma(I)]	*R*1 = 0.0286 *wR*2 = 0.0635
R indices (all data)	*R*1 = 0.0315 *wR*2 = 0.0649
Absolute structure parameter	-0.04(2)
Largest diff. peak and hole	0.587 and -0.533 eÅ^{-3}

Notes:

N2 and C11 evenly disordered with each other. Fractional occupancy atoms were refined subject to having similar coordinates and ADPs in each shared site.

George Dimery sa crystallographic author…

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) for 1.U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

Atom	x	y	z	U(eq)
Ru(1)	8343(1)	252(1)	8410(1)	23(1)
P(1)	10889(1)	5390(1)	3421(1)	38(1)
F(1)	10884(1)	4650(3)	4782(3)	79(1)
F(2)	10912(1)	6168(3)	2035(2)	66(1)
F(3)	11195(1)	4209(2)	2931(3)	67(1)
F(4)	11486(1)	5979(2)	4186(2)	48(1)
F(5)	10595(1)	6604(2)	3883(2)	53(1)
F(6)	10303(1)	4832(3)	2608(3)	92(1)
N(1)	7839(1)	400(3)	9733(2)	27(1)
N(2)	8752(1)	1804(3)	9504(3)	32(1)
N(1A)	8780(1)	-895(2)	10083(3)	25(1)
C(1)	7357(1)	1094(3)	9551(3)	31(1)
C(2)	7053(1)	1051(3)	10528(3)	35(1)
C(3)	7233(1)	327(5)	11725(3)	35(1)
C(4)	7735(1)	-361(3)	11977(3)	29(1)
C(5)	7967(1)	-1125(3)	13202(3)	35(1)
C(6)	8451(1)	-1776(3)	13377(3)	33(1)
C(7)	8750(1)	-1754(3)	12348(3)	30(1)
C(8)	9244(1)	-2448(3)	12444(3)	34(1)
C(9)	9486(1)	-2353(3)	11380(3)	34(1)
C(10)	9255(1)	-1571(3)	10212(3)	31(1)
C(11)	8780(1)	-895(2)	10083(3)	25(1)
C(12)	8530(1)	-995(3)	11148(3)	25(1)
C(13)	8025(1)	-308(3)	10964(3)	25(1)
C(14)	8946(1)	2721(3)	10050(4)	42(1)
C(15)	9198(2)	3891(4)	10747(5)	72(1)
C(16)	7671(1)	-646(3)	6763(3)	32(1)
C(17)	8164(1)	-1362(3)	6954(3)	29(1)
C(18)	8663(1)	-769(3)	6825(3)	30(1)
C(19)	8679(1)	549(3)	6551(3)	28(1)
C(20)	8174(1)	1272(3)	6379(3)	34(1)
C(21)	7679(1)	688(3)	6451(3)	33(1)
C(22)	9193(1)	1236(3)	6420(4)	37(1)
C(23)	9180(2)	1307(4)	4877(4)	50(1)
C(24)	9738(1)	653(4)	7314(4)	55(1)
C(25)	7142(1)	-1270(3)	6896(4)	39(1)
C(11A)	7839(1)	400(3)	9733(2)	27(1)

Table 3. Bond lengths [Å] and angles [°] for 1.

Ru(1)-N(2)	2.054(3)	Ru(1)-N(1)	2.080(2)
Ru(1)-N(1A)	2.093(3)	Ru(1)-C(17)	2.184(3)
Ru(1)-C(16)	2.200(3)	Ru(1)-C(20)	2.222(3)
Ru(1)-C(21)	2.225(3)	Ru(1)-C(18)	2.237(3)
Ru(1)-C(19)	2.269(3)	P(1)-F(1)	1.566(3)
P(1)-F(6)	1.573(2)	P(1)-F(4)	1.595(2)
P(1)-F(5)	1.597(2)	P(1)-F(3)	1.598(2)
P(1)-F(2)	1.620(3)	N(1)-C(1)	1.374(4)
N(1)-C(13)	1.396(4)	N(2)-C(14)	1.137(4)
N(1A)-C(10)	1.355(4)	N(1A)-C(12)	1.385(4)
C(1)-C(2)	1.400(4)	C(2)-C(3)	1.377(5)
C(3)-C(4)	1.405(5)	C(4)-C(13)	1.405(4)
C(4)-C(5)	1.437(4)	C(5)-C(6)	1.358(5)
C(6)-C(7)	1.434(4)	C(7)-C(12)	1.410(4)
C(7)-C(8)	1.411(4)	C(8)-C(9)	1.370(5)
C(9)-C(10)	1.406(4)	C(12)-C(13)	1.419(4)
C(14)-C(15)	1.455(5)	C(16)-C(17)	1.406(5)
C(16)-C(21)	1.425(5)	C(16)-C(25)	1.515(5)
C(17)-C(18)	1.434(4)	C(18)-C(19)	1.402(5)
C(19)-C(20)	1.440(4)	C(19)-C(22)	1.510(4)
C(20)-C(21)	1.402(5)	C(22)-C(24)	1.528(5)
C(22)-C(23)	1.535(5)		

N(2)-Ru(1)-N(1)	84.50(12)	N(2)-Ru(1)-N(1A)	87.46(12)
N(1)-Ru(1)-N(1A)	78.94(11)	N(2)-Ru(1)-C(17)	159.58(11)
N(1)-Ru(1)-C(17)	115.67(12)	N(1A)-Ru(1)-C(17)	93.13(11)
N(2)-Ru(1)-C(16)	153.16(12)	N(1)-Ru(1)-C(16)	91.91(12)
N(1A)-Ru(1)-C(16)	118.01(12)	C(17)-Ru(1)-C(16)	37.41(12)
N(2)-Ru(1)-C(20)	92.71(12)	N(1)-Ru(1)-C(20)	123.60(11)
N(1A)-Ru(1)-C(20)	157.39(11)	C(17)-Ru(1)-C(20)	79.02(13)
C(16)-Ru(1)-C(20)	67.25(12)	N(2)-Ru(1)-C(21)	116.29(12)
N(1)-Ru(1)-C(21)	96.12(11)	N(1A)-Ru(1)-C(21)	155.38(11)
C(17)-Ru(1)-C(21)	67.05(11)	C(16)-Ru(1)-C(21)	37.55(14)
C(20)-Ru(1)-C(21)	36.74(12)	N(2)-Ru(1)-C(18)	121.76(11)
N(1)-Ru(1)-C(18)	152.97(12)	N(1A)-Ru(1)-C(18)	94.77(11)
C(17)-Ru(1)-C(18)	37.83(11)	C(16)-Ru(1)-C(18)	67.67(12)
C(20)-Ru(1)-C(18)	66.03(12)	C(21)-Ru(1)-C(18)	78.63(12)
N(2)-Ru(1)-C(19)	94.84(11)	N(1)-Ru(1)-C(19)	161.00(10)
N(1A)-Ru(1)-C(19)	120.04(11)	C(17)-Ru(1)-C(19)	67.26(11)
C(16)-Ru(1)-C(19)	80.11(12)	C(20)-Ru(1)-C(19)	37.39(11)
C(21)-Ru(1)-C(19)	67.09(12)	C(18)-Ru(1)-C(19)	36.24(13)
F(1)-P(1)-F(6)	91.69(17)	F(1)-P(1)-F(4)	90.63(14)
F(6)-P(1)-F(4)	177.64(17)	F(1)-P(1)-F(5)	91.14(15)
F(6)-P(1)-F(5)	90.11(14)	F(4)-P(1)-F(5)	90.23(12)
F(1)-P(1)-F(3)	90.58(16)	F(6)-P(1)-F(3)	90.85(15)
F(4)-P(1)-F(3)	88.74(12)	F(5)-P(1)-F(3)	178.00(15)
F(1)-P(1)-F(2)	178.41(16)	F(6)-P(1)-F(2)	89.89(17)
F(4)-P(1)-F(2)	87.79(13)	F(5)-P(1)-F(2)	89.03(14)
F(3)-P(1)-F(2)	89.21(15)	C(1)-N(1)-C(13)	117.1(2)
C(1)-N(1)-Ru(1)	128.7(2)	C(13)-N(1)-Ru(1)	114.24(19)
C(14)-N(2)-Ru(1)	174.7(3)	C(10)-N(1A)-C(12)	117.7(3)
C(10)-N(1A)-Ru(1)	128.1(2)	C(12)-N(1A)-Ru(1)	114.16(19)

N(1)-C(1)-C(2)	121.5(3)	C(3)-C(2)-C(1)	121.0(3)
C(2)-C(3)-C(4)	119.4(3)	C(13)-C(4)-C(3)	118.1(3)
C(13)-C(4)-C(5)	118.0(3)	C(3)-C(4)-C(5)	124.0(3)
C(6)-C(5)-C(4)	121.0(3)	C(5)-C(6)-C(7)	122.0(3)
C(12)-C(7)-C(8)	117.9(3)	C(12)-C(7)-C(6)	117.5(3)
C(8)-C(7)-C(6)	124.7(3)	C(9)-C(8)-C(7)	118.9(3)
C(8)-C(9)-C(10)	121.2(3)	N(1A)-C(10)-C(9)	121.5(3)
N(1A)-C(12)-C(7)	122.9(3)	N(1A)-C(12)-C(13)	116.4(2)
C(7)-C(12)-C(13)	120.7(3)	N(1)-C(13)-C(4)	123.0(2)
N(1)-C(13)-C(12)	116.2(2)	C(4)-C(13)-C(12)	120.8(3)
N(2)-C(14)-C(15)	179.5(4)	C(17)-C(16)-C(21)	118.7(3)
C(17)-C(16)-C(25)	121.0(3)	C(21)-C(16)-C(25)	120.2(3)
C(17)-C(16)-Ru(1)	70.69(17)	C(21)-C(16)-Ru(1)	72.2(2)
C(25)-C(16)-Ru(1)	128.2(2)	C(16)-C(17)-C(18)	120.9(3)
C(16)-C(17)-Ru(1)	71.90(18)	C(18)-C(17)-Ru(1)	73.08(17)
C(19)-C(18)-C(17)	120.9(3)	C(19)-C(18)-Ru(1)	73.12(19)
C(17)-C(18)-Ru(1)	69.09(17)	C(18)-C(19)-C(20)	117.5(3)
C(18)-C(19)-C(22)	123.6(3)	C(20)-C(19)-C(22)	118.9(3)
C(18)-C(19)-Ru(1)	70.63(18)	C(20)-C(19)-Ru(1)	69.54(16)
C(22)-C(19)-Ru(1)	131.2(2)	C(21)-C(20)-C(19)	121.8(3)
C(21)-C(20)-Ru(1)	71.75(18)	C(19)-C(20)-Ru(1)	73.07(16)
C(20)-C(21)-C(16)	120.1(3)	C(20)-C(21)-Ru(1)	71.50(18)
C(16)-C(21)-Ru(1)	70.3(2)	C(19)-C(22)-C(24)	113.7(3)
C(19)-C(22)-C(23)	109.6(3)	C(24)-C(22)-C(23)	111.4(3)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2$ x 10^3) for 1. The anisotropic displacement factor exponent takes the form: $-2\ gpi^2\ [\ h^2\ a^{*2}\ U11 + ... + 2\ h\ k\ a^*\ b^*\ U$

Atom	U11	U22	U33	U23	U13	U12
Ru(1)	26(1)	23(1)	21(1)	2(1)	8(1)	1(1)
P(1)	32(1)	31(1)	47(1)	-4(1)	2(1)	-1(1)
F(1)	68(2)	79(2)	102(2)	51(2)	42(2)	18(1)
F(2)	88(2)	66(2)	40(1)	4(1)	10(1)	12(1)
F(3)	74(2)	28(1)	104(2)	-15(1)	36(2)	-2(1)
F(4)	37(1)	54(1)	50(1)	-11(1)	9(1)	-8(1)
F(5)	48(1)	50(1)	60(1)	-3(1)	14(1)	18(1)
F(6)	49(1)	85(2)	121(2)	-33(2)	-10(1)	-22(1)
N(1)	29(1)	27(2)	26(1)	2(1)	10(1)	2(1)
N(2)	32(1)	33(2)	30(1)	4(1)	7(1)	-1(1)
N(1A)	25(1)	22(1)	26(1)	-2(1)	3(1)	-2(1)
C(1)	34(2)	29(2)	30(2)	1(1)	10(1)	5(1)
C(2)	38(2)	33(2)	37(2)	-1(1)	16(1)	9(1)
C(3)	43(1)	35(2)	33(1)	0(2)	21(1)	5(2)
C(4)	38(2)	27(1)	24(1)	-4(1)	10(1)	-4(1)
C(5)	49(2)	36(2)	22(1)	-3(1)	13(1)	-5(1)
C(6)	44(2)	32(2)	21(1)	2(1)	5(1)	-4(1)
C(7)	34(2)	26(1)	26(2)	-1(1)	2(1)	-4(1)
C(8)	34(2)	31(2)	31(2)	5(1)	-0(1)	1(1)
C(9)	26(1)	34(2)	37(2)	2(1)	1(1)	4(1)
C(10)	28(2)	30(2)	32(2)	2(1)	6(1)	-0(1)
C(11)	25(1)	22(1)	26(1)	-2(1)	3(1)	-2(1)
C(12)	28(1)	22(1)	24(1)	-2(1)	6(1)	-4(1)
C(13)	32(1)	22(1)	21(1)	-3(1)	8(1)	-1(1)
C(14)	43(2)	35(2)	41(2)	1(2)	4(2)	-4(2)
C(15)	78(3)	44(2)	78(3)	-17(2)	-4(2)	-20(2)
C(16)	36(2)	37(2)	20(2)	-5(1)	4(1)	-4(1)
C(17)	39(2)	29(2)	20(1)	-2(1)	8(1)	-1(1)
C(18)	32(2)	31(2)	28(2)	-2(1)	12(1)	2(1)
C(19)	35(2)	30(2)	23(1)	3(1)	14(1)	5(1)
C(20)	44(2)	33(2)	27(2)	9(1)	14(1)	9(1)
C(21)	30(2)	38(2)	29(2)	5(1)	7(1)	7(1)
C(22)	39(2)	34(2)	44(2)	4(1)	19(1)	0(1)
C(23)	45(2)	62(2)	50(2)	10(2)	26(2)	-1(2)
C(24)	36(2)	67(3)	63(2)	21(2)	14(2)	-2(2)
C(25)	33(2)	47(2)	36(2)	-6(2)	8(1)	-7(1)
C(11A)	29(1)	27(2)	26(1)	2(1)	10(1)	2(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

Atom	x	y	z	U(eq)
H(1)	7227	1615	8743	37
H(2)	6717	1529	10363	42
H(3)	7021	293	12375	42
H(5)	7778	-1176	13901	42
H(6)	8597	-2261	14206	40
H(8)	9405	-2972	13234	41
H(9)	9816	-2824	11432	41
H(10)	9435	-1515	9496	37
H(15A)	9174	4569	10053	108
H(15B)	9590	3728	11243	108
H(15C)	9000	4163	11415	108
H(17)	8165	-2250	7172	35
H(18)	8988	-1276	6927	36
H(20)	8176	2169	6211	41
H(21)	7348	1182	6292	39
H(22)	9175	2137	6751	45
H(23A)	9249	451	4553	75
H(23B)	9470	1900	4773	75
H(23C)	8815	1615	4322	75
H(24A)	9731	609	8288	83
H(24B)	10051	1189	7249	83
H(24C)	9781	-214	6977	83
H(25A)	6903	-1494	5966	59
H(25B)	6946	-669	7344	59
H(25C)	7237	-2049	7464	59

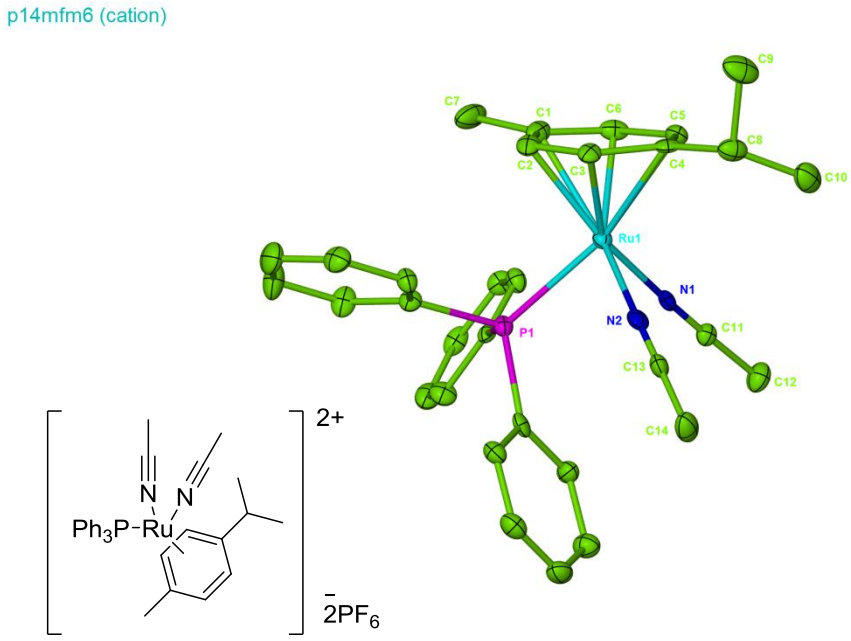


Table 1. Crystal data and structure refinement for 1.

Identification code	p14mfm6
Empirical formula	C32 H35 F12 N2 P3 Ru
Formula weight	869.60
Temperature	150(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	P21/n
Unit cell dimensions	a = 11.1395(6)Å alpha = 90°
	b = 18.8552(8)Å beta = 92.132(5)°
	c = 17.0570(11)Å gamma = 90°
Volume	3580.1(3) $Å^3$
Z	4
Density (calculated)	1.613 Mg/m^3
Absorption coefficient	0.661 mm^{-1}
F(000)	1752
Crystal size	0.1990 x 0.0654 x 0.0455 mm
Theta range for data collection	3.05 to 25.03°
Index ranges	-12<=h<=13; -17<=k<=22; -15<=l<=20
Reflections collected	21607
Independent reflections	6212 [R(int) = 0.1322]
Reflections observed (>2sigma)	3662
Data Completeness	0.981
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	1.00000 and 0.88727
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	6212 / 204 / 564
Goodness-of-fit on F^2	1.055

Final R indices [I>2sigma(I)]	R1 = 0.0751 wR2 = 0.1048
R indices (all data)	R1 = 0.1487 wR2 = 0.1300
Largest diff. peak and hole	0.563 and -0.653 eÅ^{-3}

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) for 1.U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

Atom	x	y	z	U(eq)
Ru(1)	7745(1)	1464(1)	7019(1)	25(1)
P(1)	7324(2)	2310(1)	6025(1)	26(1)
P(2)	2613(2)	654(1)	8045(2)	40(1)
P(3)	7683(2)	3795(1)	9020(2)	49(1)
F(1)	2680(20)	359(11)	8908(9)	102(8)
F(2)	1256(8)	408(6)	8007(10)	77(4)
F(3)	2507(18)	973(10)	7216(8)	96(7)
F(4)	3944(10)	862(9)	8127(14)	105(6)
F(5)	2177(15)	1380(7)	8339(14)	95(7)
F(6)	2994(13)	-96(6)	7773(11)	76(5)
F(7)	7340(20)	3424(12)	9780(11)	100(8)
F(8)	6368(16)	3900(15)	8734(15)	111(9)
F(9)	8020(30)	4238(15)	8306(15)	156(12)
F(10)	9008(14)	3726(15)	9325(14)	75(7)
F(11)	7240(20)	4460(11)	9466(19)	88(9)
F(12)	7730(20)	3061(10)	8644(18)	110(10)
F(1A)	2357(18)	91(9)	8684(10)	80(6)
F(2A)	1765(14)	332(7)	7380(10)	99(5)
F(3A)	2920(20)	1232(10)	7412(11)	112(8)
F(4A)	3549(14)	997(7)	8616(9)	81(5)
F(5A)	1620(14)	1149(9)	8365(11)	87(6)
F(6A)	3653(13)	163(8)	7742(9)	79(5)
F(7A)	6911(19)	3293(13)	9550(12)	89(7)
F(8A)	6607(17)	3850(14)	8390(10)	70(6)
F(9A)	8414(16)	4236(8)	8384(9)	52(4)
F(10A)	8837(19)	3759(16)	9593(15)	102(10)
F(11A)	7630(20)	4568(10)	9397(17)	63(6)
F(12A)	8150(20)	3114(8)	8565(12)	61(5)
N(1)	6318(5)	931(3)	6537(4)	26(2)
N(2)	6474(6)	1963(3)	7643(4)	33(2)
C(1)	9643(7)	1238(4)	6663(5)	40(2)
C(2)	9635(6)	1757(4)	7260(5)	34(2)
C(3)	9100(6)	1638(4)	7958(5)	31(2)
C(4)	8560(6)	976(4)	8135(5)	29(2)
C(5)	8537(6)	472(4)	7535(5)	33(2)
C(6)	9040(6)	603(4)	6808(5)	35(2)
C(7)	10331(7)	1352(5)	5932(6)	61(3)
C(8)	8050(7)	856(4)	8928(5)	43(2)
C(9)	9103(8)	642(5)	9484(6)	63(3)
C(10)	7048(8)	323(4)	8943(6)	57(3)
C(11)	5504(7)	626(4)	6306(5)	29(2)

C(12)	4459(7)	225(4)	6033(5)	45(2)
C(13)	5735(7)	2218(4)	7966(5)	34(2)
C(14)	4761(7)	2555(4)	8377(6)	53(3)
C(15)	8448(6)	3010(3)	5995(5)	30(2)
C(16)	8835(6)	3331(3)	6691(5)	31(2)
C(17)	9702(7)	3855(4)	6684(6)	45(2)
C(18)	10187(8)	4057(4)	5990(6)	53(3)
C(19)	9781(8)	3761(4)	5289(6)	57(3)
C(20)	8913(7)	3235(4)	5296(5)	43(2)
C(21)	5890(7)	2765(3)	6119(5)	30(2)
C(22)	4836(6)	2439(4)	5834(5)	34(2)
C(23)	3734(7)	2757(4)	5951(5)	44(2)
C(24)	3675(7)	3392(4)	6348(5)	45(2)
C(25)	4713(7)	3716(4)	6627(5)	42(2)
C(26)	5814(7)	3407(3)	6524(5)	35(2)
C(27)	7234(6)	1937(3)	5047(5)	26(2)
C(28)	7656(6)	1264(3)	4886(5)	33(2)
C(29)	7660(7)	993(4)	4143(5)	35(2)
C(30)	7196(6)	1387(4)	3528(5)	38(2)
C(31)	6733(7)	2048(4)	3667(5)	45(2)
C(32)	6737(7)	2325(4)	4414(5)	38(2)

Table 3. Bond lengths [Å] and angles [^{o}] for 1.

Ru(1)-N(1)	2.028(6)	Ru(1)-N(2)	2.034(7)
Ru(1)-C(3)	2.185(7)	Ru(1)-C(2)	2.201(7)
Ru(1)-C(6)	2.210(7)	Ru(1)-C(5)	2.234(7)
Ru(1)-C(1)	2.262(8)	Ru(1)-C(4)	2.272(7)
Ru(1)-P(1)	2.362(2)	P(1)-C(27)	1.811(8)
P(1)-C(15)	1.821(7)	P(1)-C(21)	1.825(7)
P(2)-F(4)	1.536(11)	P(2)-F(3)	1.537(12)
P(2)-F(4A)	1.543(11)	P(2)-F(5)	1.543(12)
P(2)-F(6)	1.552(11)	P(2)-F(1A)	1.555(12)
P(2)-F(5A)	1.562(12)	P(2)-F(2A)	1.570(9)
P(2)-F(1)	1.573(13)	P(2)-F(2)	1.579(9)
P(2)-F(3A)	1.583(13)	P(2)-F(6A)	1.584(10)
P(3)-F(12)	1.528(16)	P(3)-F(9)	1.536(17)
P(3)-F(7)	1.534(15)	P(3)-F(8)	1.540(16)
P(3)-F(11)	1.554(15)	P(3)-F(10)	1.552(14)
P(3)-F(8A)	1.584(14)	P(3)-F(7A)	1.584(15)
P(3)-F(10A)	1.586(15)	P(3)-F(11A)	1.595(15)
P(3)-F(12A)	1.596(14)	P(3)-F(9A)	1.612(11)
N(1)-C(11)	1.133(8)	N(2)-C(13)	1.114(9)
C(1)-C(6)	1.400(10)	C(1)-C(2)	1.412(11)
C(1)-C(7)	1.504(11)	C(2)-C(3)	1.370(11)
C(2)-H(2)	0.9500	C(3)-C(4)	1.424(9)
C(3)-H(3)	0.9500	C(4)-C(5)	1.395(10)
C(4)-C(8)	1.503(11)	C(5)-C(6)	1.401(11)
C(5)-H(5)	0.9500	C(6)-H(6)	0.9500
C(7)-H(7A)	0.9800	C(7)-H(7B)	0.9800
C(7)-H(7C)	0.9800	C(8)-C(10)	1.503(11)
C(8)-C(9)	1.534(11)	C(8)-H(8)	1.0000
C(9)-H(9A)	0.9800	C(9)-H(9B)	0.9800
C(9)-H(9C)	0.9800	C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800	C(10)-H(10C)	0.9800
C(11)-C(12)	1.451(10)	C(12)-H(12A)	0.9800
C(12)-H(12B)	0.9800	C(12)-H(12C)	0.9800
C(13)-C(14)	1.461(11)	C(14)-H(14A)	0.9800
C(14)-H(14B)	0.9800	C(14)-H(14C)	0.9800
C(15)-C(20)	1.384(11)	C(15)-C(16)	1.388(10)
C(16)-C(17)	1.382(9)	C(16)-H(16)	0.9500
C(17)-C(18)	1.372(12)	C(17)-H(17)	0.9500
C(18)-C(19)	1.382(12)	C(18)-H(18)	0.9500
C(19)-C(20)	1.385(10)	C(19)-H(19)	0.9500
C(20)-H(20)	0.9500	C(21)-C(22)	1.396(9)
C(21)-C(26)	1.398(9)	C(22)-C(23)	1.388(10)
C(22)-H(22)	0.9500	C(23)-C(24)	1.377(10)
C(23)-H(23)	0.9500	C(24)-C(25)	1.377(10)
C(24)-H(24)	0.9500	C(25)-C(26)	1.374(10)
C(25)-H(25)	0.9500	C(26)-H(26)	0.9500

C(27)-C(28)	1.383(9)	C(27)-C(32)	1.400(10)
C(28)-C(29)	1.367(11)	C(28)-H(28)	0.9500
C(29)-C(30)	1.372(11)	C(29)-H(29)	0.9500
C(30)-C(31)	1.373(10)	C(30)-H(30)	0.9500
C(31)-C(32)	1.377(11)	C(31)-H(31)	0.9500
C(32)-H(32)	0.9500		
N(1)-Ru(1)-N(2)	83.7(2)	N(1)-Ru(1)-C(3)	151.8(2)
N(2)-Ru(1)-C(3)	91.2(3)	N(1)-Ru(1)-C(2)	158.4(3)
N(2)-Ru(1)-C(2)	117.8(3)	C(3)-Ru(1)-C(2)	36.4(3)
N(1)-Ru(1)-C(6)	94.4(2)	N(2)-Ru(1)-C(6)	153.7(3)
C(3)-Ru(1)-C(6)	78.0(3)	C(2)-Ru(1)-C(6)	65.7(3)
N(1)-Ru(1)-C(5)	92.2(2)	N(2)-Ru(1)-C(5)	117.0(3)
C(3)-Ru(1)-C(5)	65.5(3)	C(2)-Ru(1)-C(5)	77.0(3)
C(6)-Ru(1)-C(5)	36.7(3)	N(1)-Ru(1)-C(1)	121.7(3)
N(2)-Ru(1)-C(1)	154.6(3)	C(3)-Ru(1)-C(1)	66.3(3)
C(2)-Ru(1)-C(1)	36.8(3)	C(6)-Ru(1)-C(1)	36.5(3)
C(5)-Ru(1)-C(1)	65.7(3)	N(1)-Ru(1)-C(4)	114.9(2)
N(2)-Ru(1)-C(4)	90.8(3)	C(3)-Ru(1)-C(4)	37.2(2)
C(2)-Ru(1)-C(4)	66.1(3)	C(6)-Ru(1)-C(4)	66.2(3)
C(5)-Ru(1)-C(4)	36.0(3)	C(1)-Ru(1)-C(4)	78.5(3)
N(1)-Ru(1)-P(1)	84.95(16)	N(2)-Ru(1)-P(1)	86.53(17)
C(3)-Ru(1)-P(1)	122.54(19)	C(2)-Ru(1)-P(1)	97.3(2)
C(6)-Ru(1)-P(1)	119.5(2)	C(5)-Ru(1)-P(1)	155.9(2)
C(1)-Ru(1)-P(1)	95.6(2)	C(4)-Ru(1)-P(1)	159.55(18)
C(27)-P(1)-C(15)	105.6(3)	C(27)-P(1)-C(21)	104.2(3)
C(15)-P(1)-C(21)	105.5(3)	C(27)-P(1)-Ru(1)	113.7(2)
C(15)-P(1)-Ru(1)	113.1(3)	C(21)-P(1)-Ru(1)	114.0(2)
F(4)-P(2)-F(3)	91.4(11)	F(4)-P(2)-F(4A)	37.6(8)
F(3)-P(2)-F(4A)	116.3(11)	F(4)-P(2)-F(5)	93.3(9)
F(3)-P(2)-F(5)	86.4(12)	F(4A)-P(2)-F(5)	68.6(9)
F(4)-P(2)-F(6)	89.2(8)	F(3)-P(2)-F(6)	95.4(10)
F(4A)-P(2)-F(6)	112.7(8)	F(5)-P(2)-F(6)	176.8(10)
F(4)-P(2)-F(1A)	108.2(10)	F(3)-P(2)-F(1A)	154.4(11)
F(4A)-P(2)-F(1A)	88.9(9)	F(5)-P(2)-F(1A)	108.0(12)
F(6)-P(2)-F(1A)	69.3(10)	F(4)-P(2)-F(5A)	120.6(10)
F(3)-P(2)-F(5A)	93.3(10)	F(4A)-P(2)-F(5A)	89.9(10)
F(5)-P(2)-F(5A)	28.3(8)	F(6)-P(2)-F(5A)	148.7(9)
F(1A)-P(2)-F(5A)	90.7(11)	F(4)-P(2)-F(2A)	135.9(12)
F(3)-P(2)-F(2A)	57.6(9)	F(4A)-P(2)-F(2A)	172.9(11)
F(5)-P(2)-F(2A)	113.0(9)	F(6)-P(2)-F(2A)	66.1(7)
F(1A)-P(2)-F(2A)	97.0(10)	F(5A)-P(2)-F(2A)	94.0(9)
F(4)-P(2)-F(1)	89.4(11)	F(3)-P(2)-F(1)	177.2(11)
F(4A)-P(2)-F(1)	63.1(9)	F(5)-P(2)-F(1)	90.8(12)
F(6)-P(2)-F(1)	87.3(10)	F(1A)-P(2)-F(1)	26.7(10)
F(5A)-P(2)-F(1)	84.0(11)	F(2A)-P(2)-F(1)	123.2(11)
F(4)-P(2)-F(2)	176.4(9)	F(3)-P(2)-F(2)	92.1(9)
F(4A)-P(2)-F(2)	140.6(10)	F(5)-P(2)-F(2)	87.8(7)
F(6)-P(2)-F(2)	89.5(8)	F(1A)-P(2)-F(2)	68.2(9)
F(5A)-P(2)-F(2)	60.1(8)	F(2A)-P(2)-F(2)	46.2(7)

F(1)-P(2)-F(2)	87.1(10)	F(4)-P(2)-F(3A)	69.6(10)
F(3)-P(2)-F(3A)	27.6(9)	F(4A)-P(2)-F(3A)	88.9(9)
F(5)-P(2)-F(3A)	71.9(12)	F(6)-P(2)-F(3A)	110.8(12)
F(1A)-P(2)-F(3A)	177.7(11)	F(5A)-P(2)-F(3A)	90.1(12)
F(2A)-P(2)-F(3A)	85.1(9)	F(1)-P(2)-F(3A)	151.4(11)
F(2)-P(2)-F(3A)	114.1(9)	F(4)-P(2)-F(6A)	57.5(8)
F(3)-P(2)-F(6A)	87.8(9)	F(4A)-P(2)-F(6A)	88.0(8)
F(5)-P(2)-F(6A)	150.1(10)	F(6)-P(2)-F(6A)	32.8(6)
F(1A)-P(2)-F(6A)	89.1(10)	F(5A)-P(2)-F(6A)	177.9(10)
F(2A)-P(2)-F(6A)	88.1(9)	F(1)-P(2)-F(6A)	95.0(10)
F(2)-P(2)-F(6A)	121.7(9)	F(3A)-P(2)-F(6A)	89.9(12)
F(12)-P(3)-F(9)	98.4(17)	F(12)-P(3)-F(7)	87.5(15)
F(9)-P(3)-F(7)	174.2(15)	F(12)-P(3)-F(8)	91.8(15)
F(9)-P(3)-F(8)	86.3(14)	F(7)-P(3)-F(8)	93.5(13)
F(12)-P(3)-F(11)	162.3(14)	F(9)-P(3)-F(11)	92.3(17)
F(7)-P(3)-F(11)	82.1(15)	F(8)-P(3)-F(11)	74.8(14)
F(12)-P(3)-F(10)	91.0(15)	F(9)-P(3)-F(10)	93.0(15)
F(7)-P(3)-F(10)	86.8(13)	F(8)-P(3)-F(10)	177.2(15)
F(11)-P(3)-F(10)	102.6(14)	F(12)-P(3)-F(8A)	79.1(15)
F(9)-P(3)-F(8A)	68.2(13)	F(7)-P(3)-F(8A)	113.3(12)
F(8)-P(3)-F(8A)	24.3(13)	F(11)-P(3)-F(8A)	91.9(14)
F(10)-P(3)-F(8A)	156.8(12)	F(12)-P(3)-F(7A)	74.1(14)
F(9)-P(3)-F(7A)	158.7(14)	F(7)-P(3)-F(7A)	24.2(13)
F(8)-P(3)-F(7A)	74.2(13)	F(11)-P(3)-F(7A)	90.9(16)
F(10)-P(3)-F(7A)	106.8(13)	F(8A)-P(3)-F(7A)	90.7(11)
F(12)-P(3)-F(10A)	100.4(15)	F(9)-P(3)-F(10A)	107.1(16)
F(7)-P(3)-F(10A)	71.5(14)	F(8)-P(3)-F(10A)	160.1(14)
F(11)-P(3)-F(10A)	89.8(15)	F(10)-P(3)-F(10A)	18.5(17)
F(8A)-P(3)-F(10A)	175.0(14)	F(7A)-P(3)-F(10A)	93.9(13)
F(12)-P(3)-F(11A)	178.9(17)	F(9)-P(3)-F(11A)	80.6(16)
F(7)-P(3)-F(11A)	93.6(15)	F(8)-P(3)-F(11A)	87.9(14)
F(11)-P(3)-F(11A)	18.2(17)	F(10)-P(3)-F(11A)	89.3(14)
F(8A)-P(3)-F(11A)	100.2(13)	F(7A)-P(3)-F(11A)	106.8(15)
F(10A)-P(3)-F(11A)	80.2(14)	F(12)-P(3)-F(12A)	18.1(16)
F(9)-P(3)-F(12A)	87.6(14)	F(7)-P(3)-F(12A)	98.0(11)
F(8)-P(3)-F(12A)	105.7(14)	F(11)-P(3)-F(12A)	179.5(14)
F(10)-P(3)-F(12A)	77.0(13)	F(8A)-P(3)-F(12A)	88.5(12)
F(7A)-P(3)-F(12A)	89.4(13)	F(10A)-P(3)-F(12A)	89.8(13)
F(11A)-P(3)-F(12A)	161.4(12)	F(12)-P(3)-F(9A)	99.1(13)
F(9)-P(3)-F(9A)	16.3(15)	F(7)-P(3)-F(9A)	162.3(11)
F(8)-P(3)-F(9A)	102.6(12)	F(11)-P(3)-F(9A)	95.1(14)
F(10)-P(3)-F(9A)	76.7(12)	F(8A)-P(3)-F(9A)	84.1(10)
F(7A)-P(3)-F(9A)	172.2(10)	F(10A)-P(3)-F(9A)	91.1(13)
F(11A)-P(3)-F(9A)	80.0(12)	F(12A)-P(3)-F(9A)	84.6(10)
C(11)-N(1)-Ru(1)	176.5(6)	C(13)-N(2)-Ru(1)	176.5(7)
C(6)-C(1)-C(2)	116.6(8)	C(6)-C(1)-C(7)	122.1(8)
C(2)-C(1)-C(7)	121.1(7)	C(6)-C(1)-Ru(1)	69.7(4)
C(2)-C(1)-Ru(1)	69.2(4)	C(7)-C(1)-Ru(1)	134.9(6)
C(3)-C(2)-C(1)	121.9(7)	C(3)-C(2)-Ru(1)	71.2(4)
C(1)-C(2)-Ru(1)	73.9(4)	C(3)-C(2)-H(2)	119.0

C(1)-C(2)-H(2)	119.0	Ru(1)-C(2)-H(2)	128.2
C(2)-C(3)-C(4)	121.9(7)	C(2)-C(3)-Ru(1)	72.5(4)
C(4)-C(3)-Ru(1)	74.8(4)	C(2)-C(3)-H(3)	119.1
C(4)-C(3)-H(3)	119.1	Ru(1)-C(3)-H(3)	125.5
C(5)-C(4)-C(3)	116.0(8)	C(5)-C(4)-C(8)	124.1(7)
C(3)-C(4)-C(8)	119.9(7)	C(5)-C(4)-Ru(1)	70.5(4)
C(3)-C(4)-Ru(1)	68.1(4)	C(8)-C(4)-Ru(1)	131.5(5)
C(4)-C(5)-C(6)	122.2(7)	C(4)-C(5)-Ru(1)	73.5(4)
C(6)-C(5)-Ru(1)	70.7(4)	C(4)-C(5)-H(5)	118.9
C(6)-C(5)-H(5)	118.9	Ru(1)-C(5)-H(5)	129.5
C(1)-C(6)-C(5)	121.2(7)	C(1)-C(6)-Ru(1)	73.8(4)
C(5)-C(6)-Ru(1)	72.6(4)	C(1)-C(6)-H(6)	119.4
C(5)-C(6)-H(6)	119.4	Ru(1)-C(6)-H(6)	126.1
C(1)-C(7)-H(7A)	109.5	C(1)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5	C(1)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7C)	109.5	H(7B)-C(7)-H(7C)	109.5
C(10)-C(8)-C(4)	114.9(7)	C(10)-C(8)-C(9)	111.4(7)
C(4)-C(8)-C(9)	106.9(7)	C(10)-C(8)-H(8)	107.8
C(4)-C(8)-H(8)	107.8	C(9)-C(8)-H(8)	107.8
C(8)-C(9)-H(9A)	109.5	C(8)-C(9)-H(9B)	109.5
H(9A)-C(9)-H(9B)	109.5	C(8)-C(9)-H(9C)	109.5
H(9A)-C(9)-H(9C)	109.5	H(9B)-C(9)-H(9C)	109.5
C(8)-C(10)-H(10A)	109.5	C(8)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5	C(8)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5	H(10B)-C(10)-H(10C)	109.5
N(1)-C(11)-C(12)	178.2(9)	C(11)-C(12)-H(12A)	109.5
C(11)-C(12)-H(12B)	109.5	H(12A)-C(12)-H(12B)	109.5
C(11)-C(12)-H(12C)	109.5	H(12A)-C(12)-H(12C)	109.5
H(12B)-C(12)-H(12C)	109.5	N(2)-C(13)-C(14)	179.2(9)
C(13)-C(14)-H(14A)	109.5	C(13)-C(14)-H(14B)	109.5
H(14A)-C(14)-H(14B)	109.5	C(13)-C(14)-H(14C)	109.5
H(14A)-C(14)-H(14C)	109.5	H(14B)-C(14)-H(14C)	109.5
C(20)-C(15)-C(16)	119.2(7)	C(20)-C(15)-P(1)	121.8(6)
C(16)-C(15)-P(1)	118.9(6)	C(17)-C(16)-C(15)	120.0(8)
C(17)-C(16)-H(16)	120.0	C(15)-C(16)-H(16)	120.0
C(18)-C(17)-C(16)	120.2(8)	C(18)-C(17)-H(17)	119.9
C(16)-C(17)-H(17)	119.9	C(17)-C(18)-C(19)	120.6(8)
C(17)-C(18)-H(18)	119.7	C(19)-C(18)-H(18)	119.7
C(18)-C(19)-C(20)	119.1(9)	C(18)-C(19)-H(19)	120.4
C(20)-C(19)-H(19)	120.4	C(15)-C(20)-C(19)	120.8(8)
C(15)-C(20)-H(20)	119.6	C(19)-C(20)-H(20)	119.6

C(22)-C(21)-C(26)	119.1(7)	C(22)-C(21)-P(1)	119.3(5)
C(26)-C(21)-P(1)	121.3(5)	C(23)-C(22)-C(21)	119.8(7)
C(23)-C(22)-H(22)	120.1	C(21)-C(22)-H(22)	120.1
C(24)-C(23)-C(22)	120.3(7)	C(24)-C(23)-H(23)	119.8
C(22)-C(23)-H(23)	119.8	C(23)-C(24)-C(25)	120.0(7)
C(23)-C(24)-H(24)	120.0	C(25)-C(24)-H(24)	120.0
C(26)-C(25)-C(24)	120.7(7)	C(26)-C(25)-H(25)	119.7
C(24)-C(25)-H(25)	119.7	C(25)-C(26)-C(21)	120.1(7)
C(25)-C(26)-H(26)	120.0	C(21)-C(26)-H(26)	120.0
C(28)-C(27)-C(32)	117.1(7)	C(28)-C(27)-P(1)	122.1(6)
C(32)-C(27)-P(1)	120.9(6)	C(29)-C(28)-C(27)	122.6(8)
C(29)-C(28)-H(28)	118.7	C(27)-C(28)-H(28)	118.7
C(28)-C(29)-C(30)	119.5(7)	C(28)-C(29)-H(29)	120.3
C(30)-C(29)-H(29)	120.3	C(29)-C(30)-C(31)	119.5(8)
C(29)-C(30)-H(30)	120.2	C(31)-C(30)-H(30)	120.2
C(30)-C(31)-C(32)	121.1(8)	C(30)-C(31)-H(31)	119.5
C(32)-C(31)-H(31)	119.5	C(31)-C(32)-C(27)	120.1(7)
C(31)-C(32)-H(32)	119.9	C(27)-C(32)-H(32)	119.9

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2$ x 10^3) for 1. The anisotropic displacement
factor exponent takes the form: -2 gpi^2 [h^2 a^{*2} U11 + ... + 2 h k a* b* U

Atom	U11	U22	U33	U23	U13	U12
Ru(1)	27(1)	27(1)	22(1)	2(1)	-2(1)	-1(1)
P(1)	28(1)	27(1)	21(1)	0(1)	-3(1)	-4(1)
P(2)	44(2)	33(1)	44(2)	-3(1)	-8(1)	9(1)
P(3)	70(2)	39(1)	37(2)	-3(1)	-1(1)	6(1)
F(1)	106(15)	123(15)	77(12)	31(10)	12(10)	55(11)
F(2)	37(6)	61(8)	131(12)	21(8)	-16(7)	-5(5)
F(3)	118(13)	114(14)	56(10)	37(9)	0(9)	46(11)
F(4)	37(7)	102(11)	175(16)	21(12)	-6(9)	-16(7)
F(5)	96(12)	50(8)	140(14)	-31(8)	20(11)	20(8)
F(6)	87(10)	56(8)	85(11)	-19(7)	-16(9)	15(7)
F(7)	125(15)	86(11)	93(14)	53(10)	65(12)	42(10)
F(8)	75(11)	82(10)	170(20)	6(15)	-32(12)	0(8)
F(9)	190(20)	143(15)	131(18)	43(13)	11(14)	68(13)
F(10)	50(8)	75(11)	99(15)	16(10)	4(8)	35(7)
F(11)	126(18)	67(12)	71(13)	-20(10)	3(13)	53(11)
F(12)	128(18)	73(11)	128(18)	-48(11)	-1(13)	-9(9)
F(1A)	74(10)	56(9)	110(14)	54(9)	24(9)	-7(7)
F(2A)	105(10)	70(8)	115(12)	-41(8)	-81(9)	4(7)
F(3A)	155(15)	90(11)	89(13)	52(9)	-28(11)	-36(9)
F(4A)	98(11)	69(8)	74(11)	-4(8)	-41(8)	-15(8)
F(5A)	82(11)	109(13)	73(10)	11(10)	16(9)	63(9)
F(6A)	87(10)	102(11)	49(9)	2(8)	10(9)	65(8)
F(7A)	90(12)	113(12)	65(12)	37(9)	14(9)	-13(8)
F(8A)	94(12)	73(9)	41(9)	8(7)	-35(8)	-21(8)
F(9A)	66(8)	35(6)	55(9)	12(5)	2(6)	-27(6)
F(10A)	134(17)	75(11)	94(16)	-14(10)	-64(13)	-4(12)
F(11A)	80(11)	57(9)	51(11)	-9(7)	-23(9)	-5(7)
F(12A)	101(13)	30(7)	55(10)	7(6)	37(9)	16(7)
N(1)	33(4)	21(3)	23(4)	7(3)	0(3)	0(3)
N(2)	36(4)	34(4)	27(5)	12(3)	-10(4)	0(3)
C(1)	32(5)	65(6)	24(6)	11(4)	-1(4)	1(4)
C(2)	28(5)	44(5)	30(6)	3(4)	-11(4)	-4(3)
C(3)	28(4)	42(5)	23(5)	3(4)	-8(4)	-1(3)
C(4)	19(4)	39(4)	27(6)	-2(4)	-10(4)	9(3)
C(5)	32(5)	29(4)	37(6)	3(4)	0(4)	5(3)
C(6)	38(5)	45(5)	22(5)	-9(4)	-8(4)	12(4)
C(7)	37(5)	103(7)	44(7)	17(6)	11(5)	14(5)
C(8)	42(5)	53(5)	34(6)	-3(4)	3(5)	15(4)
C(9)	77(7)	79(7)	32(7)	8(5)	0(5)	27(5)
C(10)	66(7)	60(6)	46(7)	11(5)	21(5)	11(5)
C(11)	31(5)	33(4)	23(5)	0(3)	2(4)	-3(3)
C(12)	43(5)	53(5)	40(7)	-4(4)	1(5)	-16(4)

C(13)	40(5)	28(4)	35(6)	11(4)	4(4)	0(4)
C(14)	59(6)	49(5)	54(7)	11(4)	27(5)	7(4)
C(15)	29(4)	37(4)	23(5)	-1(4)	-6(4)	-3(3)
C(16)	39(5)	29(4)	25(5)	1(3)	-6(4)	-8(3)
C(17)	39(5)	45(5)	51(7)	-6(4)	-11(5)	-8(4)
C(18)	50(6)	48(5)	61(8)	-1(5)	4(6)	-21(4)
C(19)	69(7)	62(6)	43(7)	1(5)	12(5)	-31(5)
C(20)	49(6)	53(5)	26(6)	-9(4)	-2(5)	-17(4)
C(21)	45(5)	24(4)	20(5)	7(3)	0(4)	-3(3)
C(22)	33(5)	28(4)	41(6)	0(4)	3(4)	0(3)
C(23)	41(5)	41(5)	49(7)	-5(4)	-4(5)	0(4)
C(24)	40(5)	48(5)	47(7)	8(4)	10(5)	13(4)
C(25)	55(6)	34(5)	39(6)	2(4)	-1(5)	6(4)
C(26)	40(5)	28(4)	34(6)	2(4)	-5(4)	1(3)
C(27)	17(4)	34(4)	25(5)	4(3)	-2(4)	-5(3)
C(28)	41(5)	28(4)	29(6)	1(3)	-5(4)	-8(3)
C(29)	36(5)	39(5)	28(6)	-13(4)	0(4)	-2(3)
C(30)	37(5)	54(5)	24(5)	-16(4)	5(4)	-16(4)
C(31)	40(5)	64(6)	31(6)	6(5)	-7(5)	-8(4)
C(32)	43(5)	44(5)	27(6)	-3(4)	-9(4)	2(4)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

Atom	x	y	z	U(eq)
H(2)	10013	2200	7176	41
H(3)	9088	2009	8335	38
H(5)	8169	26	7622	39
H(6)	8971	254	6407	42
H(7A)	10180	1833	5732	92
H(7B)	10071	1005	5533	92
H(7C)	11192	1293	6053	92
H(8)	7731	1319	9115	51
H(9A)	9473	207	9291	95
H(9B)	8807	558	10010	95
H(9C)	9700	1023	9507	95
H(10A)	6403	465	8570	85
H(10B)	6736	300	9472	85
H(10C)	7352	-145	8797	85
H(12A)	4691	-269	5941	68
H(12B)	4133	431	5543	68
H(12C)	3846	240	6430	68
H(14A)	4494	2980	8090	80
H(14B)	5047	2689	8907	80
H(14C)	4088	2223	8411	80
H(16)	8504	3191	7172	38
H(17)	9964	4077	7161	54
H(18)	10806	4403	5993	63
H(19)	10093	3916	4807	69
H(20)	8635	3027	4816	51
H(22)	4874	2001	5562	41
H(23)	3016	2536	5757	52
H(24)	2917	3606	6429	54
H(25)	4668	4157	6893	51
H(26)	6523	3630	6729	42
H(28)	7954	979	5310	40
H(29)	7983	535	4053	41
H(30)	7194	1204	3009	46
H(31)	6404	2319	3242	54
H(32)	6401	2780	4501	46

443

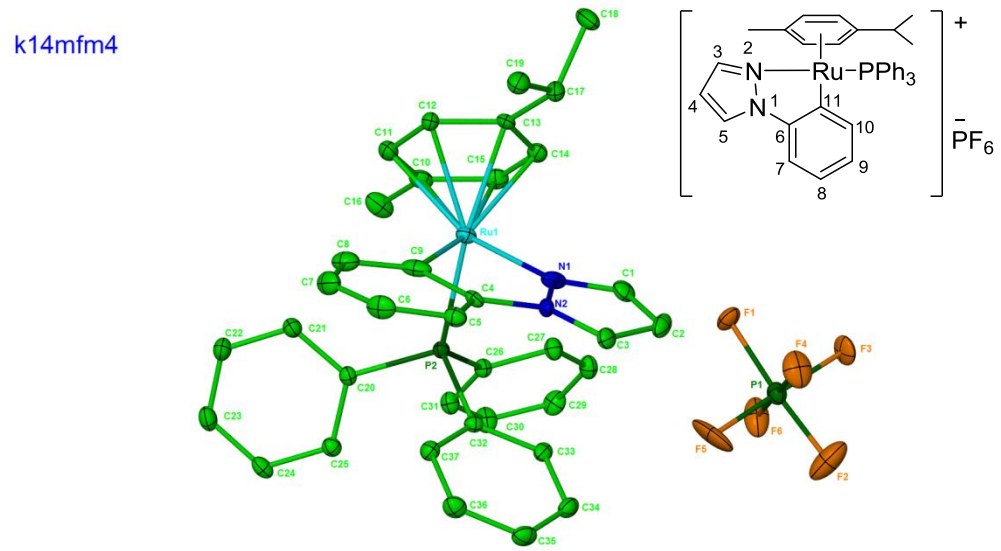


Table 1. Crystal data and structure refinement for 1.

Identification code	k14mfm4
Empirical formula	C37 H36 F6 N2 O0 P2 Ru
Formula weight	785.69
Temperature	150(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	P21/c
Unit cell dimensions	a = 14.2800(2)Å alpha = 90°
	b = 12.9900(2)Å beta = 103.858(1)°
	c = 18.9480(3)Å gamma = 90°
Volume	3412.49(9) $Å^3$
Z	4
Density (calculated)	1.529 Mg/m^3
Absorption coefficient	0.616 mm^{-1}
F(000)	1600
Crystal size	0.20 x 0.10 x 0.10 mm
Theta range for data collection	3.53 to 27.48°
Index ranges	-18<=h<=18; -16<=k<=16; -23<=l<=24
Reflections collected	60201
Independent reflections	7788 [R(int) = 0.0702]
Reflections observed (>2sigma)	5813
Data Completeness	0.997
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.897 and 0.865
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	7788 / 61 / 517
Goodness-of-fit on F^2	1.041
Final R indices [I>2sigma(I)]	*R*1 = 0.0381 *wR*2 = 0.0740
R indices (all data)	*R*1 = 0.0647 *wR*2 = 0.0825
Largest diff. peak and hole	0.458 and -0.661 $eÅ^{-3}$

Notes:

The phenyl pyrazol ligand exhibited disorder in a 65:35 ratio between the 6 and 5 membered rings. This was readily modelled, such that C1 C2 C7 and C8 were refined at full-occupancy and common to both disordered fragments. Hydrogen atoms associated with this ligand were included at calculated positions. For atoms contributing to both disordered fragments, full occupancy hydrogens were included on for relevant carbons, based only on atomic positions of the major disordered component. Some ADP restraints were also applied to minor occupancy fractional atoms, to assist convergence. The disordered N2 and C9 atoms were refined subject to having similar coordinates and ADPs in each shared site.

F1, F2, F3 and F5 also 50:50 exhibited disorder. P-F and F…F distance restraints were applied in this region, also to assist convergence.

George Dimery as crystallographic author…

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) for 1.U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

Atom	x	y	z	U(eq)
Ru(1)	2301(1)	2747(1)	1417(1)	26(1)
P(1)	2005(1)	5886(1)	-1461(1)	34(1)
P(2)	2324(1)	1727(1)	411(1)	22(1)
F(1)	1428(6)	5602(5)	-823(4)	44(2)
F(2)	2500(6)	6221(8)	-2076(5)	90(4)
F(3)	1393(8)	6912(7)	-1571(7)	60(3)
F(4)	2880(1)	6402(2)	-893(1)	68(1)
F(5)	2600(9)	4861(6)	-1355(7)	93(4)
F(6)	1134(2)	5363(2)	-2030(1)	74(1)
F(1A)	1582(8)	5727(10)	-822(6)	121(5)
F(2A)	2523(10)	5983(9)	-2095(6)	115(5)
F(3A)	1550(8)	6981(8)	-1637(7)	92(4)
F(5A)	2457(8)	4780(6)	-1270(7)	71(3)
N(1)	3196(2)	3773(2)	1042(1)	33(1)
N(2)	4124(6)	3667(5)	1218(3)	22(1)
N(1A)	3652(2)	2136(2)	1873(1)	39(1)
N(2A)	4410(12)	2479(8)	1836(8)	26(3)
C(1)	3083(2)	4607(2)	619(2)	36(1)
C(2)	3938(2)	5021(2)	530(2)	37(1)
C(3)	4630(6)	4342(5)	928(4)	32(2)
C(4)	4428(7)	2839(6)	1704(5)	22(2)
C(5)	5401(3)	2663(4)	2032(2)	30(1)
C(6)	5642(4)	1828(5)	2500(3)	40(1)
C(7)	4926(2)	1172(2)	2604(2)	43(1)
C(8)	3945(2)	1318(2)	2326(2)	42(1)
C(9)	3652(2)	2136(2)	1873(1)	39(1)
C(10)	799(2)	2233(2)	1495(2)	36(1)
C(11)	1456(2)	2087(2)	2169(2)	37(1)
C(12)	2030(2)	2914(2)	2526(1)	30(1)
C(13)	1976(2)	3899(2)	2214(1)	28(1)
C(14)	1310(2)	4024(2)	1516(1)	32(1)
C(15)	726(2)	3230(2)	1174(2)	36(1)
C(16)	134(2)	1392(2)	1125(2)	50(1)
C(17)	2574(2)	4807(2)	2559(1)	34(1)
C(18)	1933(3)	5556(2)	2857(2)	49(1)
C(19)	3464(2)	4507(2)	3144(2)	40(1)
C(20)	2321(2)	326(2)	514(1)	25(1)
C(21)	2180(2)	-143(2)	1134(2)	32(1)
C(22)	2171(2)	-1209(2)	1193(2)	40(1)
C(23)	2289(2)	-1818(2)	624(2)	38(1)
C(24)	2443(2)	-1366(2)	1(2)	34(1)
C(25)	2472(2)	-308(2)	-50(1)	28(1)
C(26)	1321(2)	1995(2)	-380(1)	24(1)
C(27)	1098(2)	3022(2)	-566(1)	31(1)
C(28)	414(2)	3275(2)	-1194(2)	35(1)
C(29)	-67(2)	2509(2)	-1640(2)	39(1)
C(30)	125(2)	1491(2)	-1453(2)	40(1)

C(31)	814(2)	1233(2)	-827(1)	32(1)
C(32)	3393(2)	1903(2)	46(1)	23(1)
C(33)	3421(2)	2644(2)	-480(1)	27(1)
C(34)	4252(2)	2785(2)	-728(1)	34(1)
C(35)	5060(2)	2192(2)	-453(2)	37(1)
C(36)	5047(2)	1464(2)	78(2)	35(1)
C(37)	4218(2)	1325(2)	328(1)	28(1)
C(3A)	5246(8)	1980(13)	2227(7)	55(4)
C(4A)	4253(10)	3378(10)	1395(7)	13(2)
C(5A)	4993(8)	3896(8)	1227(6)	44(2)
C(6A)	4780(11)	4721(10)	828(9)	44(4)
C(9A)	3196(2)	3773(2)	1042(1)	33(1)

Table 3. Bond lengths [Å] and angles [°] for 1.

Ru(1)-N(1A)	2.074(3)	Ru(1)-N(1)	2.085(2)
Ru(1)-C(14)	2.217(2)	Ru(1)-C(12)	2.236(3)
Ru(1)-C(11)	2.246(3)	Ru(1)-C(13)	2.252(2)
Ru(1)-C(15)	2.273(3)	Ru(1)-C(10)	2.285(3)
Ru(1)-P(2)	2.3292(6)	P(1)-F(1A)	1.492(9)
P(1)-F(2A)	1.560(9)	P(1)-F(2)	1.562(8)
P(1)-F(3A)	1.566(9)	P(1)-F(5)	1.567(7)
P(1)-F(3)	1.580(8)	P(1)-F(5A)	1.581(8)
P(1)-F(4)	1.5884(19)	P(1)-F(6)	1.5896(19)
P(1)-F(1)	1.659(6)	P(2)-C(20)	1.830(2)
P(2)-C(32)	1.835(2)	P(2)-C(26)	1.840(2)
N(1)-N(2)	1.294(8)	N(1)-C(1)	1.334(4)
N(2)-C(3)	1.335(10)	N(2)-C(4)	1.415(7)
N(1A)-N(2A)	1.188(15)	N(1A)-C(8)	1.367(4)
N(2A)-C(3A)	1.40(2)	N(2A)-C(4A)	1.422(12)
N(2A)-C(8)	1.968(12)	C(1)-C(2)	1.380(4)
C(2)-C(6A)	1.262(16)	C(2)-C(3)	1.402(8)
C(4)-C(5)	1.398(11)	C(5)-C(6)	1.391(8)
C(6)-C(7)	1.380(7)	C(7)-C(8)	1.386(4)
C(7)-C(3A)	1.406(17)	C(10)-C(11)	1.405(4)
C(10)-C(15)	1.424(4)	C(10)-C(16)	1.505(4)
C(11)-C(12)	1.421(4)	C(12)-C(13)	1.404(3)
C(13)-C(14)	1.440(4)	C(13)-C(17)	1.509(4)
C(14)-C(15)	1.386(4)	C(17)-C(19)	1.524(4)
C(17)-C(18)	1.533(4)	C(20)-C(21)	1.380(4)
C(20)-C(25)	1.407(3)	C(21)-C(22)	1.390(4)
C(22)-C(23)	1.379(4)	C(23)-C(24)	1.382(4)
C(24)-C(25)	1.379(4)	C(26)-C(31)	1.388(3)
C(26)-C(27)	1.398(3)	C(27)-C(28)	1.386(4)
C(28)-C(29)	1.377(4)	C(29)-C(30)	1.380(4)
C(30)-C(31)	1.389(4)	C(32)-C(37)	1.392(3)
C(32)-C(33)	1.394(3)	C(33)-C(34)	1.388(4)
C(34)-C(35)	1.381(4)	C(35)-C(36)	1.383(4)
C(36)-C(37)	1.388(4)	C(4A)-C(5A)	1.355(19)
C(5A)-C(6A)	1.304(17)		

N(1A)-Ru(1)-N(1)	78.58(11)	N(1A)-Ru(1)-C(14)	143.13(10)
N(1)-Ru(1)-C(14)	90.39(10)	N(1A)-Ru(1)-C(12)	89.90(10)
N(1)-Ru(1)-C(12)	121.07(9)	C(14)-Ru(1)-C(12)	65.80(9)
N(1A)-Ru(1)-C(11)	100.18(11)	N(1)-Ru(1)-C(11)	157.86(9)
C(14)-Ru(1)-C(11)	77.33(10)	C(12)-Ru(1)-C(11)	36.96(10)
N(1A)-Ru(1)-C(13)	107.19(9)	N(1)-Ru(1)-C(13)	92.60(9)
C(14)-Ru(1)-C(13)	37.60(9)	C(12)-Ru(1)-C(13)	36.46(9)
C(11)-Ru(1)-C(13)	66.42(9)	N(1A)-Ru(1)-C(15)	165.14(11)
N(1)-Ru(1)-C(15)	114.33(10)	C(14)-Ru(1)-C(15)	35.94(10)
C(12)-Ru(1)-C(15)	77.21(10)	C(11)-Ru(1)-C(15)	65.05(10)
C(13)-Ru(1)-C(15)	66.42(10)	N(1A)-Ru(1)-C(10)	130.92(12)
N(1)-Ru(1)-C(10)	150.49(10)	C(14)-Ru(1)-C(10)	65.49(10)
C(12)-Ru(1)-C(10)	65.90(10)	C(11)-Ru(1)-C(10)	36.12(10)
C(13)-Ru(1)-C(10)	78.68(10)	C(15)-Ru(1)-C(10)	36.41(10)
N(1A)-Ru(1)-P(2)	85.96(7)	N(1)-Ru(1)-P(2)	87.43(6)
C(14)-Ru(1)-P(2)	129.01(7)	C(12)-Ru(1)-P(2)	149.76(7)

C(11)-Ru(1)-P(2)	114.64(7)	C(13)-Ru(1)-P(2)	166.60(7)
C(15)-Ru(1)-P(2)	101.41(7)	C(10)-Ru(1)-P(2)	94.78(7)
F(1A)-P(1)-F(2A)	174.7(7)	F(1A)-P(1)-F(2)	171.0(7)
F(2A)-P(1)-F(2)	11.5(7)	F(1A)-P(1)-F(3A)	94.0(6)
F(2A)-P(1)-F(3A)	90.7(5)	F(2)-P(1)-F(3A)	80.1(6)
F(1A)-P(1)-F(5)	95.2(6)	F(2A)-P(1)-F(5)	79.9(7)
F(2)-P(1)-F(5)	90.2(4)	F(3A)-P(1)-F(5)	169.8(6)
F(1A)-P(1)-F(3)	84.5(6)	F(2A)-P(1)-F(3)	100.4(6)
F(2)-P(1)-F(3)	90.1(4)	F(3A)-P(1)-F(3)	10.7(6)
F(5)-P(1)-F(3)	179.4(7)	F(1A)-P(1)-F(5A)	84.9(6)
F(2A)-P(1)-F(5A)	90.4(5)	F(2)-P(1)-F(5A)	101.0(6)
F(3A)-P(1)-F(5A)	178.9(5)	F(5)-P(1)-F(5A)	11.2(6)
F(3)-P(1)-F(5A)	168.3(5)	F(1A)-P(1)-F(4)	85.1(5)
F(2A)-P(1)-F(4)	92.6(5)	F(2)-P(1)-F(4)	88.0(4)
F(3A)-P(1)-F(4)	88.8(5)	F(5)-P(1)-F(4)	87.5(6)
F(3)-P(1)-F(4)	93.1(6)	F(5A)-P(1)-F(4)	90.9(5)
F(1A)-P(1)-F(6)	95.0(5)	F(2A)-P(1)-F(6)	87.2(5)
F(2)-P(1)-F(6)	92.0(4)	F(3A)-P(1)-F(6)	91.5(5)
F(5)-P(1)-F(6)	92.1(6)	F(3)-P(1)-F(6)	87.3(6)
F(5A)-P(1)-F(6)	88.7(5)	F(4)-P(1)-F(6)	179.60(13)
F(1A)-P(1)-F(1)	7.9(7)	F(2A)-P(1)-F(1)	171.5(5)
F(2)-P(1)-F(1)	175.9(4)	F(3A)-P(1)-F(1)	95.9(5)
F(5)-P(1)-F(1)	93.8(4)	F(3)-P(1)-F(1)	85.9(4)
F(5A)-P(1)-F(1)	83.0(4)	F(4)-P(1)-F(1)	92.7(3)
F(6)-P(1)-F(1)	87.4(3)	C(20)-P(2)-C(32)	100.84(11)
C(20)-P(2)-C(26)	104.72(11)	C(32)-P(2)-C(26)	103.03(11)
C(20)-P(2)-Ru(1)	118.50(8)	C(32)-P(2)-Ru(1)	114.41(8)
C(26)-P(2)-Ru(1)	113.44(8)	N(2)-N(1)-C(1)	102.2(3)
N(2)-N(1)-Ru(1)	121.2(3)	C(1)-N(1)-Ru(1)	136.7(2)
N(1)-N(2)-C(3)	116.5(5)	N(1)-N(2)-C(4)	112.6(6)
C(3)-N(2)-C(4)	131.0(7)	N(2A)-N(1A)-C(8)	100.5(7)
N(2A)-N(1A)-Ru(1)	126.9(6)	C(8)-N(1A)-Ru(1)	132.4(2)
N(1A)-N(2A)-C(3A)	117.8(11)	N(1A)-N(2A)-C(4A)	109.0(12)
C(3A)-N(2A)-C(4A)	133.1(14)	N(1A)-N(2A)-C(8)	43.1(4)
C(3A)-N(2A)-C(8)	74.8(8)	C(4A)-N(2A)-C(8)	152.0(12)
N(1)-C(1)-C(2)	113.9(3)	C(6A)-C(2)-C(1)	127.0(7)
C(6A)-C(2)-C(3)	24.7(5)	C(1)-C(2)-C(3)	102.7(3)
N(2)-C(3)-C(2)	104.6(6)	C(5)-C(4)-N(2)	122.0(7)
C(6)-C(5)-C(4)	118.6(6)	C(7)-C(6)-C(5)	119.6(5)
C(6)-C(7)-C(8)	125.2(4)	C(6)-C(7)-C(3A)	29.0(4)
C(8)-C(7)-C(3A)	97.3(5)	N(1A)-C(8)-C(7)	118.3(3)
N(1A)-C(8)-N(2A)	36.4(5)	C(7)-C(8)-N(2A)	82.0(5)
C(11)-C(10)-C(15)	118.4(3)	C(11)-C(10)-C(16)	122.3(3)
C(15)-C(10)-C(16)	119.2(3)	C(11)-C(10)-Ru(1)	70.42(16)
C(15)-C(10)-Ru(1)	71.33(15)	C(16)-C(10)-Ru(1)	132.83(19)
C(10)-C(11)-C(12)	121.0(3)	C(10)-C(11)-Ru(1)	73.46(16)
C(12)-C(11)-Ru(1)	71.13(15)	C(13)-C(12)-C(11)	121.4(3)
C(13)-C(12)-Ru(1)	72.38(14)	C(11)-C(12)-Ru(1)	71.91(15)
C(12)-C(13)-C(14)	116.5(2)	C(12)-C(13)-C(17)	124.1(2)
C(14)-C(13)-C(17)	119.4(2)	C(12)-C(13)-Ru(1)	71.16(14)
C(14)-C(13)-Ru(1)	69.89(14)	C(17)-C(13)-Ru(1)	128.56(18)
C(15)-C(14)-C(13)	122.5(2)	C(15)-C(14)-Ru(1)	74.24(16)
C(13)-C(14)-Ru(1)	72.51(14)	C(14)-C(15)-C(10)	120.2(3)
C(14)-C(15)-Ru(1)	69.82(15)	C(10)-C(15)-Ru(1)	72.27(15)
C(13)-C(17)-C(19)	113.7(2)	C(13)-C(17)-C(18)	109.3(2)
C(19)-C(17)-C(18)	111.2(2)	C(21)-C(20)-C(25)	118.0(2)

C(21)-C(20)-P(2)	122.33(19)	C(25)-C(20)-P(2)	119.69(19)
C(20)-C(21)-C(22)	121.0(2)	C(23)-C(22)-C(21)	120.2(3)
C(22)-C(23)-C(24)	119.9(3)	C(25)-C(24)-C(23)	119.8(3)
C(24)-C(25)-C(20)	121.1(2)	C(31)-C(26)-C(27)	118.2(2)
C(31)-C(26)-P(2)	123.51(19)	C(27)-C(26)-P(2)	118.18(18)
C(28)-C(27)-C(26)	121.0(2)	C(29)-C(28)-C(27)	120.1(3)
C(28)-C(29)-C(30)	119.7(3)	C(29)-C(30)-C(31)	120.5(3)
C(26)-C(31)-C(30)	120.6(2)	C(37)-C(32)-C(33)	118.7(2)
C(37)-C(32)-P(2)	119.52(18)	C(33)-C(32)-P(2)	121.66(19)
C(34)-C(33)-C(32)	120.4(2)	C(35)-C(34)-C(33)	120.2(2)
C(34)-C(35)-C(36)	120.0(2)	C(35)-C(36)-C(37)	119.9(3)
C(36)-C(37)-C(32)	120.7(2)	N(2A)-C(3A)-C(7)	105.9(10)
C(5A)-C(4A)-N(2A)	121.7(12)	C(6A)-C(5A)-C(4A)	117.3(12)
C(2)-C(6A)-C(5A)	125.2(12)		

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2$ x 10^3) for 1. The anisotropic displacement factor exponent takes the form: -2 gpi^2 [h^2 a^{*2} U11 + ... + 2 h k a* b* U

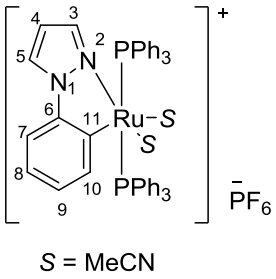
Atom	U11	U22	U33	U23	U13	U12
Ru(1)	23(1)	27(1)	28(1)	-5(1)	9(1)	1(1)
P(1)	38(1)	30(1)	32(1)	2(1)	2(1)	2(1)
P(2)	22(1)	21(1)	24(1)	-0(1)	6(1)	-0(1)
F(1)	42(3)	49(3)	45(4)	15(2)	16(2)	6(2)
F(2)	49(4)	160(8)	65(6)	50(5)	19(4)	0(4)
F(3)	55(4)	39(5)	88(6)	0(4)	21(4)	20(3)
F(4)	58(1)	60(1)	69(1)	-3(1)	-18(1)	-12(1)
F(5)	104(7)	74(7)	89(7)	-34(5)	-5(5)	68(6)
F(6)	86(2)	52(1)	59(1)	6(1)	-30(1)	-17(1)
F(1A)	81(6)	221(11)	72(6)	20(6)	37(4)	-40(5)
F(2A)	150(9)	155(8)	67(6)	-24(5)	76(6)	-30(6)
F(3A)	102(8)	31(4)	106(8)	19(4)	-50(5)	-2(4)
F(5A)	84(5)	37(4)	75(5)	25(4)	-11(4)	4(4)
N(1)	27(1)	37(1)	37(1)	-15(1)	13(1)	-7(1)
N(2)	28(3)	16(3)	20(3)	6(2)	2(2)	6(2)
N(1A)	32(2)	57(2)	28(1)	-16(1)	4(1)	11(1)
N(2A)	29(5)	24(6)	24(5)	-2(5)	4(3)	8(5)
C(1)	39(2)	26(1)	41(2)	-10(1)	9(1)	-4(1)
C(2)	53(2)	32(2)	28(1)	-0(1)	11(1)	-18(1)
C(3)	38(4)	27(4)	32(3)	-2(3)	10(3)	-7(3)
C(4)	22(3)	19(4)	24(4)	-3(3)	5(3)	4(4)
C(5)	28(2)	31(2)	32(2)	-2(2)	6(2)	3(2)
C(6)	26(3)	54(3)	35(3)	-2(3)	0(2)	15(3)
C(7)	48(2)	45(2)	34(2)	10(1)	8(1)	20(2)
C(8)	42(2)	53(2)	31(2)	-6(1)	12(1)	9(2)
C(9)	32(2)	57(2)	28(1)	-16(1)	4(1)	11(1)
C(10)	28(1)	37(2)	49(2)	-8(1)	20(1)	-1(1)
C(11)	44(2)	27(2)	46(2)	1(1)	22(1)	5(1)
C(12)	39(2)	26(1)	29(1)	3(1)	14(1)	3(1)
C(13)	36(2)	24(1)	30(1)	-3(1)	17(1)	5(1)
C(14)	31(1)	32(2)	36(2)	5(1)	14(1)	10(1)
C(15)	25(1)	46(2)	39(2)	-3(1)	10(1)	3(1)
C(16)	34(2)	45(2)	75(2)	-15(2)	19(2)	-7(1)
C(17)	52(2)	25(1)	29(1)	0(1)	15(1)	-1(1)
C(18)	74(2)	33(2)	39(2)	-4(1)	12(2)	16(2)
C(19)	50(2)	35(2)	36(2)	-4(1)	13(1)	-4(1)
C(20)	24(1)	23(1)	29(1)	1(1)	5(1)	0(1)
C(21)	35(2)	27(1)	36(2)	-2(1)	13(1)	-0(1)
C(22)	49(2)	31(2)	45(2)	9(1)	20(1)	2(1)
C(23)	39(2)	24(1)	52(2)	3(1)	13(1)	0(1)
C(24)	30(1)	25(1)	46(2)	-8(1)	8(1)	1(1)
C(25)	26(1)	27(1)	31(1)	-1(1)	7(1)	-0(1)
C(26)	21(1)	25(1)	27(1)	-0(1)	5(1)	-2(1)
C(27)	30(1)	27(1)	35(2)	-0(1)	2(1)	-3(1)
C(28)	32(2)	30(2)	42(2)	9(1)	6(1)	3(1)
C(29)	30(2)	49(2)	34(2)	9(1)	-2(1)	0(1)
C(30)	35(2)	38(2)	39(2)	-2(1)	-5(1)	-5(1)
C(31)	30(1)	28(1)	37(2)	1(1)	3(1)	-0(1)
C(32)	23(1)	24(1)	22(1)	-5(1)	5(1)	-2(1)

C(33)	32(1)	25(1)	25(1)	-3(1)	7(1)	-4(1)
C(34)	39(2)	33(2)	33(2)	0(1)	16(1)	-8(1)
C(35)	32(2)	42(2)	44(2)	-6(1)	20(1)	-6(1)
C(36)	26(1)	38(2)	43(2)	-2(1)	11(1)	2(1)
C(37)	30(1)	29(1)	27(1)	1(1)	8(1)	-1(1)
C(3A)	21(6)	94(11)	45(8)	-23(8)	0(5)	16(7)
C(4A)	8(4)	9(6)	20(6)	7(4)	-1(4)	5(4)
C(5A)	47(6)	44(5)	47(5)	-17(4)	23(4)	-15(4)
C(6A)	49(7)	43(7)	42(6)	-14(6)	14(5)	-10(6)
C(9A)	27(1)	37(1)	37(1)	-15(1)	13(1)	-7(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

Atom	x	y	z	U(eq)
H(1)	2469	4890	398	43
H(2)	4033	5617	266	45
H(3)	5308	4359	980	38
H(5)	5887	3104	1936	36
H(6)	6295	1710	2746	48
H(7)	5121	574	2890	51
H(8)	3489	860	2446	50
H(11)	1517	1426	2389	45
H(12)	2461	2798	2986	36
H(14)	1270	4674	1283	38
H(15)	277	3351	723	43
H(16A)	419	720	1284	76
H(16B)	37	1455	597	76
H(16C)	-489	1455	1254	76
H(17)	2801	5173	2166	41
H(18A)	1377	5751	2466	74
H(18B)	2305	6174	3044	74
H(18C)	1708	5224	3250	74
H(19A)	3265	4155	3541	60
H(19B)	3831	5127	3331	60
H(19C)	3870	4046	2935	60
H(21)	2089	269	1527	38
H(22)	2082	-1520	1626	49
H(23)	2266	-2546	661	46
H(24)	2528	-1783	-390	40
H(25)	2596	-2	-474	34
H(27)	1420	3555	-257	38
H(28)	276	3977	-1316	42
H(29)	-528	2682	-2075	47
H(30)	-216	963	-1755	48
H(31)	939	529	-703	39
H(33)	2869	3056	-671	33
H(34)	4265	3290	-1087	41
H(35)	5624	2283	-629	45
H(36)	5604	1060	270	42
H(37)	4215	830	696	34
H(3A)	5895	2153	2235	65
H(5A)	5641	3669	1392	53
H(6A)	5302	5129	756	53

p14cgf2



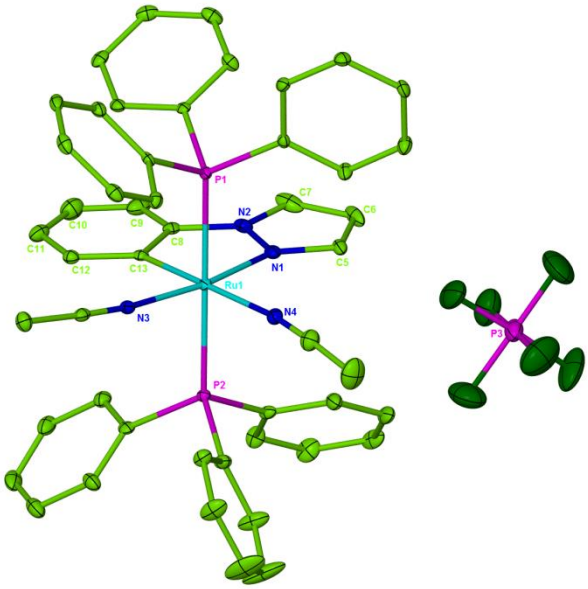


Table 1. Crystal data and structure refinement for 1.

Identification code	p14cgf2
Empirical formula	C102 H96 F12 N8 O P6 Ru2
Formula weight	2065.83
Temperature	150(2) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	P-1
Unit cell dimensions	a = 11.8790(4)Å alpha = 86.186(3)° b = 16.7735(7)Å beta = 88.782(3)° c = 24.8334(8)Å gamma = 70.548(4)°
Volume	4655.3(3) $Å^3$
Z	2
Density (calculated)	1.474 Mg/m^3
Absorption coefficient	0.506 mm^{-1}
F(000)	2116
Crystal size	0.25 x 0.16 x 0.15 mm
Theta range for data collection	3.55 to 27.48°
Index ranges	-15<=h<=15; -21<=k<=21; 0<=l<=32
Reflections collected	21273
Independent reflections	21273 [R(int) = 0.0000]
Reflections observed (>2sigma)	15225
Data Completeness	0.996
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	1.00000 and 0.78866
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	21273 / 0 / 1139
Goodness-of-fit on F^2	1.067
Final R indices [I>2sigma(I)]	R1 = 0.0569 *wR*2 = 0.1353
R indices (all data)	R1 = 0.0886 *wR*2 = 0.1529
Largest diff. peak and hole	1.517 and -0.967 $eÅ^{-3}$

Notes:

Asymmetric unit contains 2 molecules plus an area of diffuse solvent. The latter was treated with Platon SQUEEZE, and an allowance of one molecule of Et_2O per pair of ruthenium cations has been made in the formula presented herein.

George Dimery – on publication

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$ x 10^3) for 1.U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

Atom	x	y	z	U(eq)
Ru(1)	7786(1)	7625(1)	5934(1)	15(1)
Ru(2)	5407(1)	2641(1)	8781(1)	20(1)
P(1)	8781(1)	8600(1)	5640(1)	16(1)
P(2)	6773(1)	6675(1)	6236(1)	16(1)
P(3)	11276(1)	5932(1)	7847(1)	50(1)
P(4)	4115(1)	2503(1)	9494(1)	24(1)
P(5)	6756(1)	2749(1)	8074(1)	22(1)
P(6)	3744(1)	559(1)	7323(1)	34(1)
F(1)	11010(5)	6381(3)	8399(2)	117(2)
F(2)	10676(3)	6814(2)	7530(2)	80(1)
F(3)	11504(4)	5470(2)	7301(2)	91(1)
F(4)	11804(4)	5042(2)	8152(2)	112(2)
F(5)	12510(3)	6054(3)	7825(2)	110(2)
F(6)	9978(4)	5852(3)	7879(2)	102(1)
F(7)	4254(4)	1105(3)	7676(2)	102(2)
F(8)	4991(4)	-48(3)	7176(2)	110(2)
F(9)	3199(5)	68(3)	6959(2)	133(2)
F(10)	2476(3)	1216(2)	7457(2)	92(1)
F(11)	3601(5)	-18(2)	7816(2)	108(2)
F(12)	3854(4)	1165(2)	6817(2)	93(1)
N(1)	9380(3)	6650(2)	5819(1)	21(1)
N(2)	9527(3)	6372(2)	5308(1)	24(1)
N(3)	6219(3)	8587(2)	5910(1)	18(1)
N(4)	8039(3)	7795(2)	6746(1)	24(1)
N(5)	5162(3)	3876(2)	8938(2)	36(1)
N(6)	6010(4)	3934(3)	9324(2)	55(1)
N(7)	5817(3)	1368(2)	8734(2)	35(1)
N(8)	4035(3)	2942(2)	8221(1)	25(1)
C(1)	5370(3)	9164(2)	5865(2)	21(1)
C(2)	4310(3)	9925(2)	5796(2)	28(1)
C(3)	8069(4)	7874(3)	7200(2)	34(1)
C(4)	8056(6)	7975(4)	7779(2)	62(2)
C(5)	10367(3)	6189(2)	6098(2)	23(1)
C(6)	11193(4)	5626(2)	5774(2)	38(1)
C(7)	10610(4)	5755(3)	5244(2)	46(1)
C(8)	8558(3)	6750(2)	4941(2)	18(1)
C(9)	8604(4)	6480(3)	4429(2)	37(1)
C(10)	7696(5)	6835(3)	4095(2)	43(1)
C(11)	6742(4)	7457(3)	4270(2)	31(1)
C(12)	6663(3)	7726(2)	4785(2)	21(1)
C(13)	7582(3)	7381(2)	5153(2)	17(1)
C(14)	9998(3)	8678(2)	6055(2)	17(1)
C(15)	10553(3)	8041(2)	6444(2)	24(1)
C(16)	11505(4)	8079(2)	6743(2)	28(1)
C(17)	11904(3)	8764(2)	6664(2)	24(1)
C(18)	11332(3)	9415(2)	6291(2)	23(1)
C(19)	10394(3)	9370(2)	5988(2)	20(1)

C(20)	9461(3)	8427(2)	4973(2)	16(1)
C(21)	10697(3)	8119(2)	4900(2)	23(1)
C(22)	11175(4)	7956(2)	4388(2)	28(1)
C(23)	10452(4)	8108(2)	3944(2)	29(1)
C(24)	9217(4)	8401(2)	4008(2)	24(1)
C(25)	8732(3)	8562(2)	4516(2)	20(1)
C(26)	7830(3)	9719(2)	5591(2)	17(1)
C(27)	7696(3)	10255(2)	5131(2)	22(1)
C(28)	6941(3)	11102(2)	5134(2)	26(1)
C(29)	6353(3)	11408(2)	5597(2)	27(1)
C(30)	6504(3)	10886(2)	6065(2)	26(1)
C(31)	7228(3)	10046(2)	6060(2)	22(1)
C(32)	6036(3)	6863(2)	6894(2)	24(1)
C(33)	5905(5)	6192(3)	7220(2)	48(1)
C(34)	5278(7)	6330(3)	7689(3)	86(3)
C(35)	4777(6)	7138(3)	7857(2)	74(2)
C(36)	4879(4)	7819(3)	7542(2)	42(1)
C(37)	5498(3)	7680(2)	7063(2)	25(1)
C(38)	7750(3)	5575(2)	6361(2)	22(1)
C(39)	8659(4)	5437(2)	6733(2)	30(1)
C(40)	9422(4)	4623(2)	6870(2)	34(1)
C(41)	9270(4)	3944(3)	6636(2)	40(1)
C(42)	8375(4)	4076(3)	6272(2)	41(1)
C(43)	7618(4)	4883(2)	6130(2)	32(1)
C(44)	5564(3)	6585(2)	5822(2)	22(1)
C(45)	4393(3)	6808(2)	6003(2)	29(1)
C(46)	3508(4)	6683(3)	5694(2)	37(1)
C(47)	3782(4)	6340(3)	5203(2)	39(1)
C(48)	4939(4)	6137(2)	5013(2)	33(1)
C(49)	5825(4)	6261(2)	5314(2)	26(1)
C(50)	5991(4)	669(3)	8703(2)	36(1)
C(51)	6397(6)	-244(3)	8702(3)	77(2)
C(52)	3312(4)	3097(2)	7902(2)	33(1)
C(53)	2352(5)	3283(3)	7501(2)	55(2)
C(54)	4500(4)	4650(3)	8830(2)	34(1)
C(55)	4692(6)	5316(3)	9062(2)	63(2)
C(56)	5784(8)	4810(5)	9427(3)	97(3)
C(57)	6885(4)	3119(3)	9542(2)	40(1)
C(58)	7654(7)	3127(7)	9929(3)	97(3)
C(59)	8347(7)	2467(6)	10105(4)	96(3)
C(60)	8399(5)	1723(4)	9928(2)	59(2)
C(61)	7574(4)	1681(3)	9533(2)	39(1)
C(62)	6753(3)	2422(2)	9328(2)	24(1)
C(63)	3078(4)	3470(3)	9756(2)	34(1)
C(64)	2806(5)	3580(3)	10296(2)	50(1)
C(65)	1963(5)	4309(4)	10464(3)	64(2)
C(66)	1368(5)	4948(3)	10088(3)	60(2)
C(67)	1590(4)	4847(3)	9546(2)	46(1)
C(68)	2434(4)	4095(3)	9383(2)	36(1)
C(69)	3063(3)	1937(3)	9387(2)	30(1)
C(70)	2371(4)	1790(3)	9825(2)	41(1)
C(71)	1532(4)	1399(3)	9758(2)	51(1)
C(72)	1354(4)	1154(3)	9255(2)	46(1)
C(73)	2027(4)	1288(3)	8824(2)	36(1)
C(74)	2883(3)	1669(2)	8887(2)	28(1)
C(75)	4954(3)	1909(2)	10086(2)	27(1)

C(76)	5483(4)	2300(3)	10434(2)	39(1)
C(77)	6221(5)	1828(3)	10845(2)	51(1)
C(78)	6463(5)	973(3)	10904(2)	49(1)
C(79)	5993(4)	566(3)	10552(2)	45(1)
C(80)	5240(4)	1034(3)	10140(2)	36(1)
C(81)	7702(4)	1749(2)	7805(2)	26(1)
C(82)	8918(4)	1535(3)	7709(2)	34(1)
C(83)	9544(4)	794(3)	7474(2)	41(1)
C(84)	8955(4)	250(3)	7326(2)	38(1)
C(85)	7742(4)	461(3)	7415(2)	34(1)
C(86)	7115(4)	1203(2)	7648(2)	29(1)
C(87)	6028(3)	3328(2)	7449(2)	24(1)
C(88)	6323(4)	3031(3)	6944(2)	37(1)
C(89)	5743(5)	3486(3)	6488(2)	49(1)
C(90)	4863(4)	4263(3)	6525(2)	39(1)
C(91)	4538(4)	4574(3)	7028(2)	40(1)
C(92)	5112(4)	4103(2)	7483(2)	35(1)
C(93)	7807(3)	3291(2)	8234(2)	25(1)
C(94)	7698(4)	4094(3)	8017(2)	34(1)
C(95)	8469(5)	4500(3)	8162(2)	43(1)
C(96)	9386(4)	4109(3)	8518(2)	38(1)
C(97)	9522(4)	3304(3)	8739(2)	36(1)
C(98)	8731(3)	2902(3)	8603(2)	30(1)

Table 3. Bond lengths [Å] and angles [°] for 1.

Ru(1)-N(3)	2.016(3)	Ru(1)-C(13)	2.044(4)
Ru(1)-N(1)	2.079(3)	Ru(1)-N(4)	2.097(3)
Ru(1)-P(2)	2.3738(10)	Ru(1)-P(1)	2.3873(10)
Ru(2)-N(7)	2.038(4)	Ru(2)-C(62)	2.042(4)
Ru(2)-N(5)	2.056(4)	Ru(2)-N(8)	2.074(3)
Ru(2)-P(4)	2.3679(11)	Ru(2)-P(5)	2.3916(11)
P(1)-C(20)	1.826(4)	P(1)-C(26)	1.837(3)
P(1)-C(14)	1.838(4)	P(2)-C(32)	1.832(4)
P(2)-C(38)	1.834(3)	P(2)-C(44)	1.835(4)
P(3)-F(5)	1.546(4)	P(3)-F(4)	1.563(3)
P(3)-F(2)	1.575(3)	P(3)-F(3)	1.580(4)
P(3)-F(1)	1.582(4)	P(3)-F(6)	1.592(4)
P(4)-C(63)	1.830(4)	P(4)-C(75)	1.830(4)
P(4)-C(69)	1.837(5)	P(5)-C(93)	1.837(4)
P(5)-C(81)	1.839(4)	P(5)-C(87)	1.842(4)
P(6)-F(8)	1.545(4)	P(6)-F(9)	1.547(3)
P(6)-F(11)	1.551(4)	P(6)-F(7)	1.573(3)
P(6)-F(10)	1.586(4)	P(6)-F(12)	1.595(4)
N(1)-C(5)	1.347(5)	N(1)-N(2)	1.369(4)
N(2)-C(7)	1.370(5)	N(2)-C(8)	1.428(5)
N(3)-C(1)	1.143(4)	N(4)-C(3)	1.149(5)
N(5)-C(54)	1.288(5)	N(5)-N(6)	1.436(6)
N(6)-C(56)	1.444(8)	N(6)-C(57)	1.490(6)
N(7)-C(50)	1.127(5)	N(8)-C(52)	1.134(5)
C(1)-C(2)	1.467(5)	C(2)-H(2A)	0.9800
C(2)-H(2B)	0.9800	C(2)-H(2C)	0.9800
C(3)-C(4)	1.457(7)	C(4)-H(4A)	0.9800
C(4)-H(4B)	0.9800	C(4)-H(4C)	0.9800
C(5)-C(6)	1.397(6)	C(5)-H(5)	0.9500
C(6)-C(7)	1.469(7)	C(6)-H(6)	0.9500
C(7)-H(7)	0.9500	C(8)-C(9)	1.372(5)
C(8)-C(13)	1.404(5)	C(9)-C(10)	1.324(7)
C(9)-H(9)	0.9500	C(10)-C(11)	1.347(6)
C(10)-H(10)	0.9500	C(11)-C(12)	1.375(5)
C(11)-H(11)	0.9500	C(12)-C(13)	1.383(5)
C(12)-H(12)	0.9500	C(14)-C(15)	1.388(5)
C(14)-C(19)	1.391(5)	C(15)-C(16)	1.388(5)
C(15)-H(15)	0.9500	C(16)-C(17)	1.383(5)
C(16)-H(16)	0.9500	C(17)-C(18)	1.383(5)
C(17)-H(17)	0.9500	C(18)-C(19)	1.382(5)
C(18)-H(18)	0.9500	C(19)-H(19)	0.9500
C(20)-C(21)	1.397(5)	C(20)-C(25)	1.402(5)
C(21)-C(22)	1.387(6)	C(21)-H(21)	0.9500
C(22)-C(23)	1.370(6)	C(22)-H(22)	0.9500
C(23)-C(24)	1.393(6)	C(23)-H(23)	0.9500
C(24)-C(25)	1.380(5)	C(24)-H(24)	0.9500
C(25)-H(25)	0.9500	C(26)-C(27)	1.384(5)
C(26)-C(31)	1.398(5)	C(27)-C(28)	1.404(5)
C(27)-H(27)	0.9500	C(28)-C(29)	1.371(6)
C(28)-H(28)	0.9500	C(29)-C(30)	1.386(6)
C(29)-H(29)	0.9500	C(30)-C(31)	1.385(5)
C(30)-H(30)	0.9500	C(31)-H(31)	0.9500
C(32)-C(33)	1.391(6)	C(32)-C(37)	1.394(5)
C(33)-C(34)	1.360(7)	C(33)-H(33)	0.9500

C(34)-C(35)	1.375(7)	C(34)-H(34)	0.9500
C(35)-C(36)	1.378(7)	C(35)-H(35)	0.9500
C(36)-C(37)	1.377(6)	C(36)-H(36)	0.9500
C(37)-H(37)	0.9500	C(38)-C(43)	1.383(5)
C(38)-C(39)	1.386(6)	C(39)-C(40)	1.389(5)
C(39)-H(39)	0.9500	C(40)-C(41)	1.377(6)
C(40)-H(40)	0.9500	C(41)-C(42)	1.362(7)
C(41)-H(41)	0.9500	C(42)-C(43)	1.379(5)
C(42)-H(42)	0.9500	C(43)-H(43)	0.9500
C(44)-C(45)	1.387(5)	C(44)-C(49)	1.394(5)
C(45)-C(46)	1.393(6)	C(45)-H(45)	0.9500
C(46)-C(47)	1.371(7)	C(46)-H(46)	0.9500
C(47)-C(48)	1.381(6)	C(47)-H(47)	0.9500
C(48)-C(49)	1.383(6)	C(48)-H(48)	0.9500
C(49)-H(49)	0.9500	C(50)-C(51)	1.446(7)
C(51)-H(51A)	0.9800	C(51)-H(51B)	0.9800
C(51)-H(51C)	0.9800	C(52)-C(53)	1.470(6)
C(53)-H(53A)	0.9800	C(53)-H(53B)	0.9800
C(53)-H(53C)	0.9800	C(54)-C(55)	1.377(7)
C(54)-H(54)	0.9500	C(55)-C(56)	1.562(10)
C(55)-H(55)	0.9500	C(56)-H(56)	0.9500
C(57)-C(58)	1.344(9)	C(57)-C(62)	1.371(6)
C(58)-C(59)	1.199(10)	C(58)-H(58)	0.9500
C(59)-C(60)	1.331(10)	C(59)-H(59)	0.9500
C(60)-C(61)	1.424(8)	C(60)-H(60)	0.9500
C(61)-C(62)	1.373(6)	C(61)-H(61)	0.9500
C(63)-C(64)	1.383(7)	C(63)-C(68)	1.383(6)
C(64)-C(65)	1.379(7)	C(64)-H(64)	0.9500
C(65)-C(66)	1.383(8)	C(65)-H(65)	0.9500
C(66)-C(67)	1.376(8)	C(66)-H(66)	0.9500
C(67)-C(68)	1.404(6)	C(67)-H(67)	0.9500
C(68)-H(68)	0.9500	C(69)-C(74)	1.393(6)
C(69)-C(70)	1.407(6)	C(70)-C(71)	1.382(7)
C(70)-H(70)	0.9500	C(71)-C(72)	1.383(7)
C(71)-H(71)	0.9500	C(72)-C(73)	1.374(7)
C(72)-H(72)	0.9500	C(73)-C(74)	1.385(6)
C(73)-H(73)	0.9500	C(74)-H(74)	0.9500
C(75)-C(80)	1.389(6)	C(75)-C(76)	1.396(6)
C(76)-C(77)	1.380(7)	C(76)-H(76)	0.9500
C(77)-C(78)	1.365(7)	C(77)-H(77)	0.9500
C(78)-C(79)	1.377(7)	C(78)-H(78)	0.9500
C(79)-C(80)	1.389(6)	C(79)-H(79)	0.9500
C(80)-H(80)	0.9500	C(81)-C(82)	1.387(6)
C(81)-C(86)	1.400(6)	C(82)-C(83)	1.380(6)
C(82)-H(82)	0.9500	C(83)-C(84)	1.392(7)
C(83)-H(83)	0.9500	C(84)-C(85)	1.381(6)
C(84)-H(84)	0.9500	C(85)-C(86)	1.378(5)
C(85)-H(85)	0.9500	C(86)-H(86)	0.9500
C(87)-C(88)	1.375(6)	C(87)-C(92)	1.397(5)
C(88)-C(89)	1.380(6)	C(88)-H(88)	0.9500
C(89)-C(90)	1.381(6)	C(89)-H(89)	0.9500
C(90)-C(91)	1.383(6)	C(90)-H(90)	0.9500
C(91)-C(92)	1.385(6)	C(91)-H(91)	0.9500
C(92)-H(92)	0.9500	C(93)-C(94)	1.382(6)
C(93)-C(98)	1.399(6)	C(94)-C(95)	1.376(6)
C(94)-H(94)	0.9500	C(95)-C(96)	1.374(7)

C(95)-H(95)	0.9500	C(96)-C(97)	1.383(6)
C(96)-H(96)	0.9500	C(97)-C(98)	1.385(6)
C(97)-H(97)	0.9500	C(98)-H(98)	0.9500
N(3)-Ru(1)-C(13)	91.41(13)	N(3)-Ru(1)-N(1)	170.46(12)
C(13)-Ru(1)-N(1)	79.42(13)	N(3)-Ru(1)-N(4)	91.35(12)
C(13)-Ru(1)-N(4)	176.46(12)	N(1)-Ru(1)-N(4)	97.91(12)
N(3)-Ru(1)-P(2)	89.71(9)	C(13)-Ru(1)-P(2)	89.91(10)
N(1)-Ru(1)-P(2)	92.88(9)	N(4)-Ru(1)-P(2)	87.90(9)
N(3)-Ru(1)-P(1)	89.47(9)	C(13)-Ru(1)-P(1)	90.82(10)
N(1)-Ru(1)-P(1)	88.05(9)	N(4)-Ru(1)-P(1)	91.41(9)
P(2)-Ru(1)-P(1)	178.91(3)	N(7)-Ru(2)-C(62)	89.65(16)
N(7)-Ru(2)-N(5)	170.83(15)	C(62)-Ru(2)-N(5)	81.47(16)
N(7)-Ru(2)-N(8)	93.79(14)	C(62)-Ru(2)-N(8)	176.45(14)
N(5)-Ru(2)-N(8)	95.13(14)	N(7)-Ru(2)-P(4)	85.66(10)
C(62)-Ru(2)-P(4)	89.44(11)	N(5)-Ru(2)-P(4)	91.95(11)
N(8)-Ru(2)-P(4)	91.69(10)	N(7)-Ru(2)-P(5)	93.29(10)
C(62)-Ru(2)-P(5)	89.33(11)	N(5)-Ru(2)-P(5)	88.89(11)
N(8)-Ru(2)-P(5)	89.60(10)	P(4)-Ru(2)-P(5)	178.39(4)
C(20)-P(1)-C(26)	104.01(16)	C(20)-P(1)-C(14)	102.97(16)
C(26)-P(1)-C(14)	99.55(15)	C(20)-P(1)-Ru(1)	114.30(11)
C(26)-P(1)-Ru(1)	115.01(12)	C(14)-P(1)-Ru(1)	118.84(12)
C(32)-P(2)-C(38)	100.17(17)	C(32)-P(2)-C(44)	101.08(18)
C(38)-P(2)-C(44)	103.65(17)	C(32)-P(2)-Ru(1)	115.96(13)
C(38)-P(2)-Ru(1)	114.24(13)	C(44)-P(2)-Ru(1)	119.13(13)
F(5)-P(3)-F(4)	91.8(3)	F(5)-P(3)-F(2)	91.5(2)
F(4)-P(3)-F(2)	176.5(2)	F(5)-P(3)-F(3)	92.5(3)
F(4)-P(3)-F(3)	88.0(2)	F(2)-P(3)-F(3)	90.7(2)
F(5)-P(3)-F(1)	89.5(3)	F(4)-P(3)-F(1)	91.3(3)
F(2)-P(3)-F(1)	89.9(2)	F(3)-P(3)-F(1)	177.9(3)
F(5)-P(3)-F(6)	177.3(3)	F(4)-P(3)-F(6)	90.1(3)
F(2)-P(3)-F(6)	86.6(2)	F(3)-P(3)-F(6)	89.5(3)
F(1)-P(3)-F(6)	88.5(3)	C(63)-P(4)-C(75)	104.7(2)
C(63)-P(4)-C(69)	99.23(19)	C(75)-P(4)-C(69)	102.2(2)
C(63)-P(4)-Ru(2)	118.20(16)	C(75)-P(4)-Ru(2)	111.42(13)
C(69)-P(4)-Ru(2)	118.91(14)	C(93)-P(5)-C(81)	104.34(18)
C(93)-P(5)-C(87)	103.48(18)	C(81)-P(5)-C(87)	100.42(17)
C(93)-P(5)-Ru(2)	115.48(13)	C(81)-P(5)-Ru(2)	116.61(14)
C(87)-P(5)-Ru(2)	114.56(13)	F(8)-P(6)-F(9)	88.0(3)
F(8)-P(6)-F(11)	93.7(2)	F(9)-P(6)-F(11)	89.2(3)
F(8)-P(6)-F(7)	94.0(3)	F(9)-P(6)-F(7)	176.8(3)
F(11)-P(6)-F(7)	93.1(3)	F(8)-P(6)-F(10)	177.3(3)
F(9)-P(6)-F(10)	92.8(3)	F(11)-P(6)-F(10)	88.9(2)
F(7)-P(6)-F(10)	85.1(2)	F(8)-P(6)-F(12)	87.7(2)
F(9)-P(6)-F(12)	90.4(2)	F(11)-P(6)-F(12)	178.5(3)
F(7)-P(6)-F(12)	87.2(2)	F(10)-P(6)-F(12)	89.7(2)
C(5)-N(1)-N(2)	106.6(3)	C(5)-N(1)-Ru(1)	139.3(3)
N(2)-N(1)-Ru(1)	114.1(2)	N(1)-N(2)-C(7)	112.1(4)
N(1)-N(2)-C(8)	116.6(3)	C(7)-N(2)-C(8)	131.3(4)
C(1)-N(3)-Ru(1)	174.5(3)	C(3)-N(4)-Ru(1)	173.0(4)
C(54)-N(5)-N(6)	104.3(4)	C(54)-N(5)-Ru(2)	143.8(3)
N(6)-N(5)-Ru(2)	111.9(3)	N(5)-N(6)-C(56)	109.6(5)
N(5)-N(6)-C(57)	116.6(4)	C(56)-N(6)-C(57)	133.8(5)
C(50)-N(7)-Ru(2)	176.9(4)	C(52)-N(8)-Ru(2)	177.7(4)
N(3)-C(1)-C(2)	177.7(4)	C(1)-C(2)-H(2A)	109.5
C(1)-C(2)-H(2B)	109.5	H(2A)-C(2)-H(2B)	109.5

C(1)-C(2)-H(2C)	109.5	H(2A)-C(2)-H(2C)	109.5
H(2B)-C(2)-H(2C)	109.5	N(4)-C(3)-C(4)	177.6(5)
C(3)-C(4)-H(4A)	109.5	C(3)-C(4)-H(4B)	109.5
H(4A)-C(4)-H(4B)	109.5	C(3)-C(4)-H(4C)	109.5
H(4A)-C(4)-H(4C)	109.5	H(4B)-C(4)-H(4C)	109.5
N(1)-C(5)-C(6)	111.6(4)	N(1)-C(5)-H(5)	124.2
C(6)-C(5)-H(5)	124.2	C(5)-C(6)-C(7)	104.7(3)
C(5)-C(6)-H(6)	127.7	C(7)-C(6)-H(6)	127.7
N(2)-C(7)-C(6)	105.0(4)	N(2)-C(7)-H(7)	127.5
C(6)-C(7)-H(7)	127.5	C(9)-C(8)-C(13)	124.4(4)
C(9)-C(8)-N(2)	120.6(3)	C(13)-C(8)-N(2)	115.0(3)
C(10)-C(9)-C(8)	119.9(4)	C(10)-C(9)-H(9)	120.1
C(8)-C(9)-H(9)	120.1	C(9)-C(10)-C(11)	118.5(5)
C(9)-C(10)-H(10)	120.7	C(11)-C(10)-H(10)	120.7
C(10)-C(11)-C(12)	122.7(4)	C(10)-C(11)-H(11)	118.6
C(12)-C(11)-H(11)	118.6	C(11)-C(12)-C(13)	121.4(4)
C(11)-C(12)-H(12)	119.3	C(13)-C(12)-H(12)	119.3
C(12)-C(13)-C(8)	113.0(3)	C(12)-C(13)-Ru(1)	132.2(3)
C(8)-C(13)-Ru(1)	114.8(3)	C(15)-C(14)-C(19)	118.2(3)
C(15)-C(14)-P(1)	120.7(3)	C(19)-C(14)-P(1)	121.1(3)
C(16)-C(15)-C(14)	120.9(4)	C(16)-C(15)-H(15)	119.5
C(14)-C(15)-H(15)	119.5	C(17)-C(16)-C(15)	120.2(4)
C(17)-C(16)-H(16)	119.9	C(15)-C(16)-H(16)	119.9
C(18)-C(17)-C(16)	119.2(4)	C(18)-C(17)-H(17)	120.4
C(16)-C(17)-H(17)	120.4	C(19)-C(18)-C(17)	120.4(4)
C(19)-C(18)-H(18)	119.8	C(17)-C(18)-H(18)	119.8
C(18)-C(19)-C(14)	120.9(3)	C(18)-C(19)-H(19)	119.5
C(14)-C(19)-H(19)	119.5	C(21)-C(20)-C(25)	118.0(3)
C(21)-C(20)-P(1)	122.2(3)	C(25)-C(20)-P(1)	119.7(3)
C(22)-C(21)-C(20)	120.3(4)	C(22)-C(21)-H(21)	119.8
C(20)-C(21)-H(21)	119.8	C(23)-C(22)-C(21)	121.1(4)
C(23)-C(22)-H(22)	119.5	C(21)-C(22)-H(22)	119.5
C(22)-C(23)-C(24)	119.5(4)	C(22)-C(23)-H(23)	120.2
C(24)-C(23)-H(23)	120.2	C(25)-C(24)-C(23)	119.8(4)
C(25)-C(24)-H(24)	120.1	C(23)-C(24)-H(24)	120.1
C(24)-C(25)-C(20)	121.2(3)	C(24)-C(25)-H(25)	119.4
C(20)-C(25)-H(25)	119.4	C(27)-C(26)-C(31)	118.5(3)
C(27)-C(26)-P(1)	124.6(3)	C(31)-C(26)-P(1)	116.8(3)
C(26)-C(27)-C(28)	120.4(4)	C(26)-C(27)-H(27)	119.8
C(28)-C(27)-H(27)	119.8	C(29)-C(28)-C(27)	120.1(4)
C(29)-C(28)-H(28)	119.9	C(27)-C(28)-H(28)	119.9
C(28)-C(29)-C(30)	120.2(3)	C(28)-C(29)-H(29)	119.9
C(30)-C(29)-H(29)	119.9	C(31)-C(30)-C(29)	119.7(4)
C(31)-C(30)-H(30)	120.2	C(29)-C(30)-H(30)	120.2
C(30)-C(31)-C(26)	121.0(4)	C(30)-C(31)-H(31)	119.5
C(26)-C(31)-H(31)	119.5	C(33)-C(32)-C(37)	117.8(4)
C(33)-C(32)-P(2)	120.4(3)	C(37)-C(32)-P(2)	121.6(3)
C(34)-C(33)-C(32)	121.0(4)	C(34)-C(33)-H(33)	119.5
C(32)-C(33)-H(33)	119.5	C(33)-C(34)-C(35)	120.6(5)
C(33)-C(34)-H(34)	119.7	C(35)-C(34)-H(34)	119.7
C(34)-C(35)-C(36)	120.1(5)	C(34)-C(35)-H(35)	120.0
C(36)-C(35)-H(35)	120.0	C(37)-C(36)-C(35)	119.4(4)
C(37)-C(36)-H(36)	120.3	C(35)-C(36)-H(36)	120.3
C(36)-C(37)-C(32)	121.2(4)	C(36)-C(37)-H(37)	119.4
C(32)-C(37)-H(37)	119.4	C(43)-C(38)-C(39)	118.5(3)
C(43)-C(38)-P(2)	125.2(3)	C(39)-C(38)-P(2)	116.2(3)

C(38)-C(39)-C(40)	120.7(4)	C(38)-C(39)-H(39)	119.6
C(40)-C(39)-H(39)	119.6	C(41)-C(40)-C(39)	119.7(4)
C(41)-C(40)-H(40)	120.2	C(39)-C(40)-H(40)	120.2
C(42)-C(41)-C(40)	119.8(4)	C(42)-C(41)-H(41)	120.1
C(40)-C(41)-H(41)	120.1	C(41)-C(42)-C(43)	120.9(4)
C(41)-C(42)-H(42)	119.5	C(43)-C(42)-H(42)	119.5
C(42)-C(43)-C(38)	120.4(4)	C(42)-C(43)-H(43)	119.8
C(38)-C(43)-H(43)	119.8	C(45)-C(44)-C(49)	118.3(4)
C(45)-C(44)-P(2)	122.2(3)	C(49)-C(44)-P(2)	119.5(3)
C(44)-C(45)-C(46)	120.9(4)	C(44)-C(45)-H(45)	119.5
C(46)-C(45)-H(45)	119.5	C(47)-C(46)-C(45)	120.3(4)
C(47)-C(46)-H(46)	119.9	C(45)-C(46)-H(46)	119.9
C(46)-C(47)-C(48)	119.3(4)	C(46)-C(47)-H(47)	120.4
C(48)-C(47)-H(47)	120.4	C(47)-C(48)-C(49)	121.1(4)
C(47)-C(48)-H(48)	119.5	C(49)-C(48)-H(48)	119.5
C(48)-C(49)-C(44)	120.2(4)	C(48)-C(49)-H(49)	119.9
C(44)-C(49)-H(49)	119.9	N(7)-C(50)-C(51)	170.9(6)
C(50)-C(51)-H(51A)	109.5	C(50)-C(51)-H(51B)	109.5
H(51A)-C(51)-H(51B)	109.5	C(50)-C(51)-H(51C)	109.5
H(51A)-C(51)-H(51C)	109.5	H(51B)-C(51)-H(51C)	109.5
N(8)-C(52)-C(53)	178.0(5)	C(52)-C(53)-H(53A)	109.5
C(52)-C(53)-H(53B)	109.5	H(53A)-C(53)-H(53B)	109.5
C(52)-C(53)-H(53C)	109.5	H(53A)-C(53)-H(53C)	109.5
H(53B)-C(53)-H(53C)	109.5	N(5)-C(54)-C(55)	122.0(5)
N(5)-C(54)-H(54)	119.0	C(55)-C(54)-H(54)	119.0
C(54)-C(55)-C(56)	99.2(4)	C(54)-C(55)-H(55)	130.4
C(56)-C(55)-H(55)	130.4	N(6)-C(56)-C(55)	104.8(5)
N(6)-C(56)-H(56)	127.6	C(55)-C(56)-H(56)	127.6
C(58)-C(57)-C(62)	127.3(6)	C(58)-C(57)-N(6)	119.4(6)
C(62)-C(57)-N(6)	113.3(4)	C(59)-C(58)-C(57)	118.8(10)
C(59)-C(58)-H(58)	120.6	C(57)-C(58)-H(58)	120.6
C(58)-C(59)-C(60)	122.9(10)	C(58)-C(59)-H(59)	118.6
C(60)-C(59)-H(59)	118.6	C(59)-C(60)-C(61)	120.2(6)
C(59)-C(60)-H(60)	119.9	C(61)-C(60)-H(60)	119.9
C(62)-C(61)-C(60)	118.7(5)	C(62)-C(61)-H(61)	120.7
C(60)-C(61)-H(61)	120.7	C(57)-C(62)-C(61)	112.0(4)
C(57)-C(62)-Ru(2)	116.8(3)	C(61)-C(62)-Ru(2)	131.2(3)
C(64)-C(63)-C(68)	117.9(4)	C(64)-C(63)-P(4)	124.6(4)
C(68)-C(63)-P(4)	117.1(3)	C(65)-C(64)-C(63)	121.5(5)
C(65)-C(64)-H(64)	119.3	C(63)-C(64)-H(64)	119.3
C(64)-C(65)-C(66)	120.0(5)	C(64)-C(65)-H(65)	120.0
C(66)-C(65)-H(65)	120.0	C(67)-C(66)-C(65)	120.0(5)
C(67)-C(66)-H(66)	120.0	C(65)-C(66)-H(66)	120.0
C(66)-C(67)-C(68)	119.2(5)	C(66)-C(67)-H(67)	120.4
C(68)-C(67)-H(67)	120.4	C(63)-C(68)-C(67)	121.2(5)
C(63)-C(68)-H(68)	119.4	C(67)-C(68)-H(68)	119.4
C(74)-C(69)-C(70)	118.0(4)	C(74)-C(69)-P(4)	123.2(3)
C(70)-C(69)-P(4)	118.8(4)	C(71)-C(70)-C(69)	120.8(5)
C(71)-C(70)-H(70)	119.6	C(69)-C(70)-H(70)	119.6
C(70)-C(71)-C(72)	120.0(5)	C(70)-C(71)-H(71)	120.0
C(72)-C(71)-H(71)	120.0	C(73)-C(72)-C(71)	119.8(5)
C(73)-C(72)-H(72)	120.1	C(71)-C(72)-H(72)	120.1
C(72)-C(73)-C(74)	120.7(5)	C(72)-C(73)-H(73)	119.7
C(74)-C(73)-H(73)	119.7	C(73)-C(74)-C(69)	120.6(4)
C(73)-C(74)-H(74)	119.7	C(69)-C(74)-H(74)	119.7
C(80)-C(75)-C(76)	118.9(4)	C(80)-C(75)-P(4)	119.7(3)

C(76)-C(75)-P(4)	120.5(3)	C(77)-C(76)-C(75)	120.2(4)
C(77)-C(76)-H(76)	119.9	C(75)-C(76)-H(76)	119.9
C(78)-C(77)-C(76)	120.2(5)	C(78)-C(77)-H(77)	119.9
C(76)-C(77)-H(77)	119.9	C(77)-C(78)-C(79)	120.7(4)
C(77)-C(78)-H(78)	119.6	C(79)-C(78)-H(78)	119.6
C(78)-C(79)-C(80)	119.7(5)	C(78)-C(79)-H(79)	120.2
C(80)-C(79)-H(79)	120.2	C(75)-C(80)-C(79)	120.2(4)
C(75)-C(80)-H(80)	119.9	C(79)-C(80)-H(80)	119.9
C(82)-C(81)-C(86)	118.5(4)	C(82)-C(81)-P(5)	124.9(3)
C(86)-C(81)-P(5)	116.4(3)	C(83)-C(82)-C(81)	120.9(4)
C(83)-C(82)-H(82)	119.5	C(81)-C(82)-H(82)	119.5
C(82)-C(83)-C(84)	120.1(4)	C(82)-C(83)-H(83)	120.0
C(84)-C(83)-H(83)	120.0	C(85)-C(84)-C(83)	119.5(4)
C(85)-C(84)-H(84)	120.3	C(83)-C(84)-H(84)	120.3
C(86)-C(85)-C(84)	120.5(4)	C(86)-C(85)-H(85)	119.8
C(84)-C(85)-H(85)	119.8	C(85)-C(86)-C(81)	120.5(4)
C(85)-C(86)-H(86)	119.7	C(81)-C(86)-H(86)	119.7
C(88)-C(87)-C(92)	117.4(4)	C(88)-C(87)-P(5)	123.5(3)
C(92)-C(87)-P(5)	119.1(3)	C(87)-C(88)-C(89)	121.3(4)
C(87)-C(88)-H(88)	119.4	C(89)-C(88)-H(88)	119.4
C(88)-C(89)-C(90)	120.9(4)	C(88)-C(89)-H(89)	119.6
C(90)-C(89)-H(89)	119.6	C(89)-C(90)-C(91)	119.2(4)
C(89)-C(90)-H(90)	120.4	C(91)-C(90)-H(90)	120.4
C(90)-C(91)-C(92)	119.4(4)	C(90)-C(91)-H(91)	120.3
C(92)-C(91)-H(91)	120.3	C(91)-C(92)-C(87)	121.9(4)
C(91)-C(92)-H(92)	119.0	C(87)-C(92)-H(92)	119.0
C(94)-C(93)-C(98)	117.9(4)	C(94)-C(93)-P(5)	122.3(3)
C(98)-C(93)-P(5)	119.7(3)	C(95)-C(94)-C(93)	121.1(4)
C(95)-C(94)-H(94)	119.4	C(93)-C(94)-H(94)	119.4
C(96)-C(95)-C(94)	120.7(4)	C(96)-C(95)-H(95)	119.6
C(94)-C(95)-H(95)	119.6	C(95)-C(96)-C(97)	119.5(4)
C(95)-C(96)-H(96)	120.3	C(97)-C(96)-H(96)	120.3
C(96)-C(97)-C(98)	119.9(4)	C(96)-C(97)-H(97)	120.0
C(98)-C(97)-H(97)	120.0	C(97)-C(98)-C(93)	120.9(4)
C(97)-C(98)-H(98)	119.6	C(93)-C(98)-H(98)	119.6

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2$ x 10^3) for 1. The anisotropic displacement factor exponent takes the form: -2 gpi^2 [h^2 a^{*2} U11 + ... + 2 h k a* b* U

Atom	U11	U22	U33	U23	U13	U12
Ru(1)	15(1)	11(1)	18(1)	2(1)	0(1)	-4(1)
Ru(2)	21(1)	22(1)	17(1)	4(1)	-1(1)	-7(1)
P(1)	16(1)	12(1)	19(1)	2(1)	-1(1)	-5(1)
P(2)	16(1)	12(1)	18(1)	1(1)	2(1)	-4(1)
P(3)	45(1)	42(1)	64(1)	22(1)	-20(1)	-20(1)
P(4)	22(1)	24(1)	21(1)	3(1)	2(1)	-4(1)
P(5)	26(1)	22(1)	19(1)	4(1)	2(1)	-9(1)
P(6)	44(1)	35(1)	29(1)	-6(1)	-2(1)	-19(1)
F(1)	189(5)	102(3)	67(3)	-5(2)	-8(3)	-56(3)
F(2)	73(2)	58(2)	92(3)	36(2)	-3(2)	-5(2)
F(3)	103(3)	73(2)	78(3)	5(2)	-20(2)	-4(2)
F(4)	160(4)	54(2)	118(4)	39(2)	-74(3)	-34(2)
F(5)	60(2)	106(3)	175(5)	13(3)	-26(3)	-43(2)
F(6)	74(3)	94(3)	153(4)	8(3)	10(3)	-49(2)
F(7)	114(3)	123(3)	97(3)	-60(3)	-2(3)	-64(3)
F(8)	94(3)	94(3)	100(3)	-5(2)	34(3)	24(2)
F(9)	230(6)	207(5)	54(3)	-29(3)	9(3)	-192(5)
F(10)	62(2)	79(2)	116(4)	24(2)	24(2)	-7(2)
F(11)	201(5)	42(2)	50(2)	13(2)	45(3)	-5(2)
F(12)	156(4)	55(2)	77(3)	-5(2)	51(3)	-49(2)
N(1)	18(2)	14(1)	30(2)	2(1)	1(1)	-6(1)
N(2)	19(2)	21(2)	35(2)	-4(1)	8(1)	-7(1)
N(3)	18(2)	15(1)	20(2)	0(1)	1(1)	-5(1)
N(4)	26(2)	15(2)	30(2)	4(1)	-1(2)	-7(1)
N(5)	48(2)	41(2)	25(2)	-3(2)	10(2)	-23(2)
N(6)	63(3)	64(3)	47(3)	-3(2)	1(2)	-34(2)
N(7)	38(2)	36(2)	28(2)	4(2)	14(2)	-8(2)
N(8)	32(2)	20(2)	24(2)	2(1)	0(2)	-11(1)
C(1)	26(2)	21(2)	20(2)	1(2)	0(2)	-14(2)
C(2)	20(2)	23(2)	35(2)	-4(2)	0(2)	-1(2)
C(3)	39(2)	27(2)	33(3)	0(2)	-3(2)	-8(2)
C(4)	75(4)	70(4)	32(3)	-12(3)	-2(3)	-12(3)
C(5)	18(2)	16(2)	35(2)	2(2)	-3(2)	-6(2)
C(6)	21(2)	18(2)	71(4)	8(2)	-7(2)	-4(2)
C(7)	34(2)	21(2)	86(4)	-15(2)	17(3)	-14(2)
C(8)	21(2)	15(2)	20(2)	-3(1)	5(2)	-9(1)
C(9)	52(3)	39(2)	29(3)	-2(2)	5(2)	-27(2)
C(10)	54(3)	40(3)	37(3)	-4(2)	6(2)	-17(2)
C(11)	41(2)	34(2)	24(2)	1(2)	0(2)	-20(2)
C(12)	21(2)	18(2)	26(2)	1(2)	0(2)	-9(2)
C(13)	20(2)	13(2)	20(2)	1(1)	3(2)	-10(1)
C(14)	14(2)	16(2)	20(2)	-1(1)	0(1)	-2(1)
C(15)	27(2)	16(2)	30(2)	2(2)	-6(2)	-10(2)
C(16)	31(2)	22(2)	32(2)	8(2)	-11(2)	-11(2)
C(17)	18(2)	22(2)	31(2)	-2(2)	-5(2)	-5(2)
C(18)	24(2)	22(2)	26(2)	0(2)	3(2)	-11(2)
C(19)	21(2)	19(2)	20(2)	4(1)	-2(2)	-8(2)
C(20)	17(2)	10(2)	22(2)	4(1)	1(2)	-6(1)
C(21)	19(2)	19(2)	32(2)	-7(2)	0(2)	-6(2)

C(22)	22(2)	25(2)	41(3)	-14(2)	7(2)	-10(2)
C(23)	40(2)	19(2)	31(2)	-6(2)	12(2)	-13(2)
C(24)	38(2)	14(2)	23(2)	5(2)	-4(2)	-11(2)
C(25)	19(2)	16(2)	28(2)	2(2)	1(2)	-8(2)
C(26)	10(2)	12(2)	30(2)	-2(1)	-1(2)	-5(1)
C(27)	18(2)	15(2)	31(2)	0(2)	-2(2)	-6(2)
C(28)	26(2)	19(2)	34(2)	9(2)	-10(2)	-11(2)
C(29)	24(2)	14(2)	42(3)	-2(2)	-9(2)	-5(2)
C(30)	18(2)	22(2)	38(2)	-10(2)	3(2)	-7(2)
C(31)	24(2)	19(2)	23(2)	1(2)	-5(2)	-8(2)
C(32)	24(2)	25(2)	24(2)	1(2)	6(2)	-9(2)
C(33)	66(3)	20(2)	47(3)	-4(2)	34(3)	-3(2)
C(34)	144(6)	28(3)	72(4)	3(3)	77(4)	-15(3)
C(35)	108(5)	46(3)	53(4)	-5(3)	56(4)	-8(3)
C(36)	52(3)	24(2)	37(3)	-2(2)	22(2)	4(2)
C(37)	26(2)	19(2)	25(2)	-1(2)	6(2)	-1(2)
C(38)	21(2)	15(2)	26(2)	4(2)	8(2)	-3(2)
C(39)	27(2)	24(2)	37(3)	6(2)	-2(2)	-9(2)
C(40)	23(2)	25(2)	47(3)	17(2)	-3(2)	-1(2)
C(41)	38(3)	17(2)	51(3)	10(2)	15(2)	7(2)
C(42)	53(3)	19(2)	46(3)	-4(2)	4(2)	-3(2)
C(43)	38(2)	20(2)	31(2)	-5(2)	-1(2)	-2(2)
C(44)	21(2)	14(2)	31(2)	4(2)	1(2)	-8(2)
C(45)	21(2)	21(2)	45(3)	1(2)	-2(2)	-6(2)
C(46)	24(2)	31(2)	59(3)	7(2)	-7(2)	-12(2)
C(47)	40(3)	34(2)	51(3)	10(2)	-18(2)	-24(2)
C(48)	44(3)	29(2)	30(2)	5(2)	-7(2)	-19(2)
C(49)	32(2)	21(2)	28(2)	2(2)	-1(2)	-13(2)
C(50)	37(2)	40(3)	33(3)	5(2)	12(2)	-16(2)
C(51)	72(4)	45(3)	98(5)	16(3)	42(4)	-3(3)
C(52)	40(2)	25(2)	34(3)	3(2)	-11(2)	-11(2)
C(53)	71(4)	34(2)	55(4)	10(2)	-39(3)	-11(2)
C(54)	33(2)	35(2)	32(3)	6(2)	8(2)	-12(2)
C(55)	99(5)	32(3)	56(4)	-8(2)	46(4)	-22(3)
C(56)	157(8)	143(7)	48(4)	-51(5)	45(5)	-119(6)
C(57)	41(3)	60(3)	28(3)	0(2)	-3(2)	-31(2)
C(58)	69(5)	160(8)	74(6)	25(5)	-14(4)	-58(5)
C(59)	68(5)	130(8)	96(7)	-6(6)	12(5)	-41(5)
C(60)	32(3)	76(4)	55(4)	11(3)	6(3)	0(3)
C(61)	37(2)	48(3)	29(3)	11(2)	5(2)	-12(2)
C(62)	18(2)	36(2)	17(2)	12(2)	-5(2)	-10(2)
C(63)	27(2)	32(2)	39(3)	-6(2)	7(2)	-2(2)
C(64)	48(3)	52(3)	37(3)	-4(2)	9(2)	2(2)
C(65)	58(4)	62(4)	57(4)	-20(3)	11(3)	1(3)
C(66)	45(3)	44(3)	75(4)	-21(3)	13(3)	7(3)
C(67)	26(2)	32(2)	73(4)	-1(2)	8(2)	-2(2)
C(68)	30(2)	31(2)	46(3)	1(2)	4(2)	-8(2)
C(69)	22(2)	32(2)	33(2)	9(2)	4(2)	-6(2)
C(70)	29(2)	60(3)	36(3)	6(2)	3(2)	-19(2)
C(71)	36(3)	69(3)	54(4)	9(3)	13(2)	-28(3)
C(72)	25(2)	54(3)	62(4)	7(3)	0(2)	-21(2)
C(73)	29(2)	32(2)	44(3)	9(2)	-5(2)	-8(2)
C(74)	21(2)	26(2)	33(2)	7(2)	1(2)	-5(2)
C(75)	23(2)	31(2)	21(2)	6(2)	4(2)	-2(2)
C(76)	48(3)	38(2)	26(2)	-8(2)	2(2)	-5(2)
C(77)	61(3)	67(3)	21(2)	-6(2)	-8(2)	-14(3)

C(78)	54(3)	59(3)	31(3)	18(2)	-11(2)	-16(3)
C(79)	45(3)	43(3)	47(3)	22(2)	-14(2)	-17(2)
C(80)	34(2)	36(2)	37(3)	12(2)	-2(2)	-12(2)
C(81)	31(2)	22(2)	21(2)	4(2)	1(2)	-6(2)
C(82)	34(2)	30(2)	36(3)	-1(2)	6(2)	-8(2)
C(83)	33(2)	42(3)	40(3)	0(2)	11(2)	-3(2)
C(84)	46(3)	31(2)	31(3)	-4(2)	8(2)	-3(2)
C(85)	48(3)	29(2)	24(2)	-1(2)	3(2)	-11(2)
C(86)	34(2)	31(2)	21(2)	4(2)	2(2)	-12(2)
C(87)	27(2)	27(2)	18(2)	7(2)	0(2)	-12(2)
C(88)	41(3)	33(2)	26(2)	2(2)	4(2)	0(2)
C(89)	65(3)	44(3)	22(2)	0(2)	-2(2)	2(3)
C(90)	43(3)	39(2)	28(2)	7(2)	-3(2)	-3(2)
C(91)	47(3)	30(2)	32(3)	6(2)	4(2)	-1(2)
C(92)	47(3)	25(2)	23(2)	0(2)	8(2)	0(2)
C(93)	29(2)	27(2)	20(2)	2(2)	7(2)	-12(2)
C(94)	47(3)	36(2)	26(2)	8(2)	-6(2)	-22(2)
C(95)	69(3)	40(2)	33(3)	6(2)	-8(2)	-35(2)
C(96)	45(3)	41(3)	37(3)	-14(2)	13(2)	-27(2)
C(97)	30(2)	43(3)	37(3)	-2(2)	6(2)	-15(2)
C(98)	25(2)	26(2)	38(3)	3(2)	3(2)	-7(2)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

Atom	x	y	z	U(eq)
H(2A)	4429	10384	5986	41
H(2B)	3611	9801	5945	41
H(2C)	4182	10097	5411	41
H(4A)	7237	8111	7914	93
H(4B)	8358	8436	7848	93
H(4C)	8565	7448	7964	93
H(5)	10487	6240	6470	28
H(6)	11961	5246	5874	45
H(7)	10916	5471	4927	55
H(9)	9285	6039	4315	45
H(10)	7718	6655	3739	52
H(11)	6097	7720	4028	37
H(12)	5962	8159	4890	25
H(15)	10277	7572	6506	29
H(16)	11885	7632	7002	33
H(17)	12564	8788	6865	28
H(18)	11585	9896	6242	28
H(19)	10015	9819	5730	24
H(21)	11213	8021	5202	28
H(22)	12017	7735	4345	34
H(23)	10791	8014	3594	35
H(24)	8710	8490	3704	29
H(25)	7889	8767	4556	25
H(27)	8117	10050	4812	26
H(28)	6838	11463	4814	31
H(29)	5840	11980	5596	32
H(30)	6112	11103	6388	31
H(31)	7318	9687	6380	26
H(33)	6259	5629	7113	57
H(34)	5185	5865	7902	103
H(35)	4361	7227	8190	89
H(36)	4526	8378	7655	51
H(37)	5559	8150	6843	30
H(39)	8761	5905	6896	36
H(40)	10045	4535	7124	41
H(41)	9788	3386	6728	48
H(42)	8271	3606	6112	50
H(43)	7003	4963	5873	38
H(45)	4192	7049	6343	35
H(46)	2712	6836	5825	45
H(47)	3183	6244	4995	47
H(48)	5129	5907	4670	39
H(49)	6613	6126	5175	31
H(51A)	6317	-484	9066	116
H(51B)	7235	-451	8591	116
H(51C)	5912	-417	8450	116
H(53A)	2408	3731	7238	82
H(53B)	1576	3471	7683	82
H(53C)	2431	2771	7313	82

H(54)	3860	4765	8581	40
H(55)	4282	5908	9015	75
H(56)	6207	5031	9665	117
H(58)	7648	3647	10062	117
H(59)	8882	2475	10381	115
H(60)	8990	1219	10067	71
H(61)	7590	1151	9413	47
H(64)	3208	3145	10558	60
H(65)	1792	4371	10837	77
H(66)	806	5458	10204	71
H(67)	1176	5281	9286	55
H(68)	2565	4014	9009	44
H(70)	2483	1963	10171	49
H(71)	1078	1298	10059	61
H(72)	768	893	9208	55
H(73)	1903	1119	8479	43
H(74)	3352	1748	8586	33
H(76)	5334	2893	10388	47
H(77)	6562	2100	11087	61
H(78)	6962	654	11192	59
H(79)	6183	-32	10591	54
H(80)	4919	755	9894	43
H(82)	9326	1904	7808	40
H(83)	10377	655	7412	49
H(84)	9384	-263	7166	46
H(85)	7336	91	7315	41
H(86)	6279	1346	7702	35
H(88)	6937	2503	6908	44
H(89)	5952	3261	6145	58
H(90)	4484	4581	6209	47
H(91)	3928	5104	7062	48
H(92)	4875	4314	7828	42
H(94)	7081	4370	7764	41
H(95)	8365	5057	8014	52
H(96)	9923	4390	8612	45
H(97)	10157	3027	8984	43
H(98)	8817	2354	8763	37

Table 6. Dihedral angles [°] for 1.

Atom1 - Atom2 - Atom3 - Atom4	Dihedral
N(3) - Ru(1) - P(1) - C(20)	-114.42(15)
C(13) - Ru(1) - P(1) - C(20)	-23.02(15)
N(1) - Ru(1) - P(1) - C(20)	56.37(15)
N(4) - Ru(1) - P(1) - C(20)	154.24(14)
P(2) - Ru(1) - P(1) - C(20)	-155.3(19)
N(3) - Ru(1) - P(1) - C(26)	5.81(16)
C(13) - Ru(1) - P(1) - C(26)	97.22(16)
N(1) - Ru(1) - P(1) - C(26)	176.60(16)
N(4) - Ru(1) - P(1) - C(26)	-85.53(16)
P(2) - Ru(1) - P(1) - C(26)	-35.1(19)
N(3) - Ru(1) - P(1) - C(14)	123.58(15)
C(13) - Ru(1) - P(1) - C(14)	-145.01(15)
N(1) - Ru(1) - P(1) - C(14)	-65.63(15)
N(4) - Ru(1) - P(1) - C(14)	32.24(14)
P(2) - Ru(1) - P(1) - C(14)	82.7(19)
N(3) - Ru(1) - P(2) - C(32)	-63.56(16)
C(13) - Ru(1) - P(2) - C(32)	-154.97(17)
N(1) - Ru(1) - P(2) - C(32)	125.63(17)
N(4) - Ru(1) - P(2) - C(32)	27.81(16)
P(1) - Ru(1) - P(2) - C(32)	-22.7(19)
N(3) - Ru(1) - P(2) - C(38)	-179.32(16)
C(13) - Ru(1) - P(2) - C(38)	89.27(17)
N(1) - Ru(1) - P(2) - C(38)	9.87(17)
N(4) - Ru(1) - P(2) - C(38)	-87.95(16)
P(1) - Ru(1) - P(2) - C(38)	-138.4(19)
N(3) - Ru(1) - P(2) - C(44)	57.51(16)
C(13) - Ru(1) - P(2) - C(44)	-33.91(16)
N(1) - Ru(1) - P(2) - C(44)	-113.31(16)
N(4) - Ru(1) - P(2) - C(44)	148.87(16)
P(1) - Ru(1) - P(2) - C(44)	98.4(19)
N(7) - Ru(2) - P(4) - C(63)	-170.4(2)
C(62) - Ru(2) - P(4) - C(63)	99.9(2)
N(5) - Ru(2) - P(4) - C(63)	18.5(2)
N(8) - Ru(2) - P(4) - C(63)	-76.69(19)
P(5) - Ru(2) - P(4) - C(63)	140.1(13)
N(7) - Ru(2) - P(4) - C(75)	68.33(18)
C(62) - Ru(2) - P(4) - C(75)	-21.36(19)
N(5) - Ru(2) - P(4) - C(75)	-102.81(18)
N(8) - Ru(2) - P(4) - C(75)	162.00(17)
P(5) - Ru(2) - P(4) - C(75)	18.8(14)
N(7) - Ru(2) - P(4) - C(69)	-50.09(18)
C(62) - Ru(2) - P(4) - C(69)	-139.78(18)
N(5) - Ru(2) - P(4) - C(69)	138.78(18)
N(8) - Ru(2) - P(4) - C(69)	43.59(16)
P(5) - Ru(2) - P(4) - C(69)	-99.6(14)
N(7) - Ru(2) - P(5) - C(93)	-128.37(18)
C(62) - Ru(2) - P(5) - C(93)	-38.76(18)
N(5) - Ru(2) - P(5) - C(93)	42.72(18)
N(8) - Ru(2) - P(5) - C(93)	137.86(16)

P(4) - Ru(2) - P(5) - C(93)	-78.9(14)
N(7) - Ru(2) - P(5) - C(81)	-5.31(18)
C(62) - Ru(2) - P(5) - C(81)	84.30(19)
N(5) - Ru(2) - P(5) - C(81)	165.78(18)
N(8) - Ru(2) - P(5) - C(81)	-99.08(17)
P(4) - Ru(2) - P(5) - C(81)	44.2(14)
N(7) - Ru(2) - P(5) - C(87)	111.52(18)
C(62) - Ru(2) - P(5) - C(87)	-158.87(18)
N(5) - Ru(2) - P(5) - C(87)	-77.39(18)
N(8) - Ru(2) - P(5) - C(87)	17.75(16)
P(4) - Ru(2) - P(5) - C(87)	161.0(13)
N(3) - Ru(1) - N(1) - C(5)	165.5(6)
C(13) - Ru(1) - N(1) - C(5)	-178.3(4)
N(4) - Ru(1) - N(1) - C(5)	-0.6(4)
P(2) - Ru(1) - N(1) - C(5)	-88.9(4)
P(1) - Ru(1) - N(1) - C(5)	90.5(4)
N(3) - Ru(1) - N(1) - N(2)	-13.4(8)
C(13) - Ru(1) - N(1) - N(2)	2.9(2)
N(4) - Ru(1) - N(1) - N(2)	-179.5(2)
P(2) - Ru(1) - N(1) - N(2)	92.2(2)
P(1) - Ru(1) - N(1) - N(2)	-88.3(2)
C(5) - N(1) - N(2) - C(7)	-1.8(4)
Ru(1) - N(1) - N(2) - C(7)	177.4(3)
C(5) - N(1) - N(2) - C(8)	177.5(3)
Ru(1) - N(1) - N(2) - C(8)	-3.3(4)
C(13) - Ru(1) - N(3) - C(1)	-63(3)
N(1) - Ru(1) - N(3) - C(1)	-47(3)
N(4) - Ru(1) - N(3) - C(1)	119(3)
P(2) - Ru(1) - N(3) - C(1)	-153(3)
P(1) - Ru(1) - N(3) - C(1)	28(3)
N(3) - Ru(1) - N(4) - C(3)	58(3)
C(13) - Ru(1) - N(4) - C(3)	-83(3)
N(1) - Ru(1) - N(4) - C(3)	-124(3)
P(2) - Ru(1) - N(4) - C(3)	-31(3)
P(1) - Ru(1) - N(4) - C(3)	148(3)
N(7) - Ru(2) - N(5) - C(54)	-163.3(8)
C(62) - Ru(2) - N(5) - C(54)	-177.7(5)
N(8) - Ru(2) - N(5) - C(54)	3.3(5)
P(4) - Ru(2) - N(5) - C(54)	-88.6(5)
P(5) - Ru(2) - N(5) - C(54)	92.8(5)
N(7) - Ru(2) - N(5) - N(6)	14.4(11)
C(62) - Ru(2) - N(5) - N(6)	0.0(3)
N(8) - Ru(2) - N(5) - N(6)	-179.0(3)
P(4) - Ru(2) - N(5) - N(6)	89.1(3)
P(5) - Ru(2) - N(5) - N(6)	-89.5(3)
C(54) - N(5) - N(6) - C(56)	-0.3(5)
Ru(2) - N(5) - N(6) - C(56)	-178.9(4)
C(54) - N(5) - N(6) - C(57)	178.1(4)
Ru(2) - N(5) - N(6) - C(57)	-0.5(5)
C(62) - Ru(2) - N(7) - C(50)	149(7)
N(5) - Ru(2) - N(7) - C(50)	135(7)
N(8) - Ru(2) - N(7) - C(50)	-32(7)
P(4) - Ru(2) - N(7) - C(50)	60(7)
P(5) - Ru(2) - N(7) - C(50)	-121(7)
N(7) - Ru(2) - N(8) - C(52)	-71(8)
C(62) - Ru(2) - N(8) - C(52)	95(8)

N(5) - Ru(2) - N(8) - C(52)	112(8)
P(4) - Ru(2) - N(8) - C(52)	-156(8)
P(5) - Ru(2) - N(8) - C(52)	23(8)
Ru(1) - N(3) - C(1) - C(2)	-18(13)
Ru(1) - N(4) - C(3) - C(4)	-12(13)
N(2) - N(1) - C(5) - C(6)	2.2(4)
Ru(1) - N(1) - C(5) - C(6)	-176.8(3)
N(1) - C(5) - C(6) - C(7)	-1.7(5)
N(1) - N(2) - C(7) - C(6)	0.8(4)
C(8) - N(2) - C(7) - C(6)	-178.4(4)
C(5) - C(6) - C(7) - N(2)	0.5(5)
N(1) - N(2) - C(8) - C(9)	-176.7(3)
C(7) - N(2) - C(8) - C(9)	2.5(6)
N(1) - N(2) - C(8) - C(13)	1.6(5)
C(7) - N(2) - C(8) - C(13)	-179.2(4)
C(13) - C(8) - C(9) - C(10)	1.6(7)
N(2) - C(8) - C(9) - C(10)	179.8(4)
C(8) - C(9) - C(10) - C(11)	-0.2(7)
C(9) - C(10) - C(11) - C(12)	-1.2(7)
C(10) - C(11) - C(12) - C(13)	1.4(6)
C(11) - C(12) - C(13) - C(8)	0.0(5)
C(11) - C(12) - C(13) - Ru(1)	179.3(3)
C(9) - C(8) - C(13) - C(12)	-1.4(5)
N(2) - C(8) - C(13) - C(12)	-179.7(3)
C(9) - C(8) - C(13) - Ru(1)	179.1(3)
N(2) - C(8) - C(13) - Ru(1)	0.9(4)
N(3) - Ru(1) - C(13) - C(12)	-3.9(4)
N(1) - Ru(1) - C(13) - C(12)	178.7(4)
N(4) - Ru(1) - C(13) - C(12)	137(2)
P(2) - Ru(1) - C(13) - C(12)	85.8(3)
P(1) - Ru(1) - C(13) - C(12)	-93.4(3)
N(3) - Ru(1) - C(13) - C(8)	175.3(3)
N(1) - Ru(1) - C(13) - C(8)	-2.0(3)
N(4) - Ru(1) - C(13) - C(8)	-43(2)
P(2) - Ru(1) - C(13) - C(8)	-94.9(3)
P(1) - Ru(1) - C(13) - C(8)	85.9(3)
C(20) - P(1) - C(14) - C(15)	-109.9(3)
C(26) - P(1) - C(14) - C(15)	143.2(3)
Ru(1) - P(1) - C(14) - C(15)	17.6(3)
C(20) - P(1) - C(14) - C(19)	69.6(3)
C(26) - P(1) - C(14) - C(19)	-37.3(3)
Ru(1) - P(1) - C(14) - C(19)	-162.9(3)
C(19) - C(14) - C(15) - C(16)	-2.3(6)
P(1) - C(14) - C(15) - C(16)	177.3(3)
C(14) - C(15) - C(16) - C(17)	1.1(6)
C(15) - C(16) - C(17) - C(18)	1.0(6)
C(16) - C(17) - C(18) - C(19)	-1.9(6)
C(17) - C(18) - C(19) - C(14)	0.7(6)
C(15) - C(14) - C(19) - C(18)	1.4(5)
P(1) - C(14) - C(19) - C(18)	-178.2(3)
C(26) - P(1) - C(20) - C(21)	124.1(3)
C(14) - P(1) - C(20) - C(21)	20.7(3)
Ru(1) - P(1) - C(20) - C(21)	-109.7(3)
C(26) - P(1) - C(20) - C(25)	-59.3(3)
C(14) - P(1) - C(20) - C(25)	-162.8(3)
Ru(1) - P(1) - C(20) - C(25)	66.9(3)

C(25) - C(20) - C(21) - C(22)	0.1(5)
P(1) - C(20) - C(21) - C(22)	176.7(3)
C(20) - C(21) - C(22) - C(23)	1.3(6)
C(21) - C(22) - C(23) - C(24)	-2.4(6)
C(22) - C(23) - C(24) - C(25)	2.1(5)
C(23) - C(24) - C(25) - C(20)	-0.7(5)
C(21) - C(20) - C(25) - C(24)	-0.4(5)
P(1) - C(20) - C(25) - C(24)	-177.1(3)
C(20) - P(1) - C(26) - C(27)	1.2(4)
C(14) - P(1) - C(26) - C(27)	107.3(3)
Ru(1) - P(1) - C(26) - C(27)	-124.5(3)
C(20) - P(1) - C(26) - C(31)	-177.2(3)
C(14) - P(1) - C(26) - C(31)	-71.1(3)
Ru(1) - P(1) - C(26) - C(31)	57.1(3)
C(31) - C(26) - C(27) - C(28)	-1.9(5)
P(1) - C(26) - C(27) - C(28)	179.7(3)
C(26) - C(27) - C(28) - C(29)	1.5(6)
C(27) - C(28) - C(29) - C(30)	0.3(6)
C(28) - C(29) - C(30) - C(31)	-1.7(6)
C(29) - C(30) - C(31) - C(26)	1.2(6)
C(27) - C(26) - C(31) - C(30)	0.6(5)
P(1) - C(26) - C(31) - C(30)	179.1(3)
C(38) - P(2) - C(32) - C(33)	-26.9(4)
C(44) - P(2) - C(32) - C(33)	79.3(4)
Ru(1) - P(2) - C(32) - C(33)	-150.4(4)
C(38) - P(2) - C(32) - C(37)	158.9(3)
C(44) - P(2) - C(32) - C(37)	-94.9(3)
Ru(1) - P(2) - C(32) - C(37)	35.4(4)
C(37) - C(32) - C(33) - C(34)	-0.3(8)
P(2) - C(32) - C(33) - C(34)	-174.7(5)
C(32) - C(33) - C(34) - C(35)	-1.3(11)
C(33) - C(34) - C(35) - C(36)	1.8(12)
C(34) - C(35) - C(36) - C(37)	-0.8(10)
C(35) - C(36) - C(37) - C(32)	-0.9(8)
C(33) - C(32) - C(37) - C(36)	1.4(7)
P(2) - C(32) - C(37) - C(36)	175.7(4)
C(32) - P(2) - C(38) - C(43)	110.6(4)
C(44) - P(2) - C(38) - C(43)	6.5(4)
Ru(1) - P(2) - C(38) - C(43)	-124.7(3)
C(32) - P(2) - C(38) - C(39)	-66.8(3)
C(44) - P(2) - C(38) - C(39)	-170.9(3)
Ru(1) - P(2) - C(38) - C(39)	57.9(3)
C(43) - C(38) - C(39) - C(40)	0.2(6)
P(2) - C(38) - C(39) - C(40)	177.7(3)
C(38) - C(39) - C(40) - C(41)	-0.3(7)
C(39) - C(40) - C(41) - C(42)	0.1(7)
C(40) - C(41) - C(42) - C(43)	0.4(7)
C(41) - C(42) - C(43) - C(38)	-0.5(7)
C(39) - C(38) - C(43) - C(42)	0.3(6)
P(2) - C(38) - C(43) - C(42)	-177.1(4)
C(32) - P(2) - C(44) - C(45)	11.8(3)
C(38) - P(2) - C(44) - C(45)	115.2(3)
Ru(1) - P(2) - C(44) - C(45)	-116.5(3)
C(32) - P(2) - C(44) - C(49)	-166.4(3)
C(38) - P(2) - C(44) - C(49)	-62.9(3)
Ru(1) - P(2) - C(44) - C(49)	65.3(3)

C(49) - C(44) - C(45) - C(46)	2.3(6)
P(2) - C(44) - C(45) - C(46)	-175.9(3)
C(44) - C(45) - C(46) - C(47)	-0.4(6)
C(45) - C(46) - C(47) - C(48)	-1.3(6)
C(46) - C(47) - C(48) - C(49)	1.0(6)
C(47) - C(48) - C(49) - C(44)	1.0(6)
C(45) - C(44) - C(49) - C(48)	-2.6(5)
P(2) - C(44) - C(49) - C(48)	175.6(3)
Ru(2) - N(7) - C(50) - C(51)	-166(5)
Ru(2) - N(8) - C(52) - C(53)	133(13)
N(6) - N(5) - C(54) - C(55)	0.7(6)
Ru(2) - N(5) - C(54) - C(55)	178.5(4)
N(5) - C(54) - C(55) - C(56)	-0.8(6)
N(5) - N(6) - C(56) - C(55)	-0.1(6)
C(57) - N(6) - C(56) - C(55)	-178.1(5)
C(54) - C(55) - C(56) - N(6)	0.5(6)
N(5) - N(6) - C(57) - C(58)	-175.9(5)
C(56) - N(6) - C(57) - C(58)	2.0(9)
N(5) - N(6) - C(57) - C(62)	1.0(6)
C(56) - N(6) - C(57) - C(62)	178.9(6)
C(62) - C(57) - C(58) - C(59)	2.9(12)
N(6) - C(57) - C(58) - C(59)	179.3(7)
C(57) - C(58) - C(59) - C(60)	0.8(13)
C(58) - C(59) - C(60) - C(61)	-3.1(12)
C(59) - C(60) - C(61) - C(62)	1.9(8)
C(58) - C(57) - C(62) - C(61)	-3.7(8)
N(6) - C(57) - C(62) - C(61)	179.7(4)
C(58) - C(57) - C(62) - Ru(2)	175.6(5)
N(6) - C(57) - C(62) - Ru(2)	-1.0(5)
C(60) - C(61) - C(62) - C(57)	1.1(6)
C(60) - C(61) - C(62) - Ru(2)	-178.1(4)
N(7) - Ru(2) - C(62) - C(57)	-177.2(3)
N(5) - Ru(2) - C(62) - C(57)	0.6(3)
N(8) - Ru(2) - C(62) - C(57)	17(2)
P(4) - Ru(2) - C(62) - C(57)	-91.5(3)
P(5) - Ru(2) - C(62) - C(57)	89.5(3)
N(7) - Ru(2) - C(62) - C(61)	2.0(4)
N(5) - Ru(2) - C(62) - C(61)	179.7(4)
N(8) - Ru(2) - C(62) - C(61)	-164(2)
P(4) - Ru(2) - C(62) - C(61)	87.7(4)
P(5) - Ru(2) - C(62) - C(61)	-91.3(4)
C(75) - P(4) - C(63) - C(64)	-15.4(5)
C(69) - P(4) - C(63) - C(64)	89.8(5)
Ru(2) - P(4) - C(63) - C(64)	-140.1(4)
C(75) - P(4) - C(63) - C(68)	171.6(4)
C(69) - P(4) - C(63) - C(68)	-83.1(4)
Ru(2) - P(4) - C(63) - C(68)	46.9(4)
C(68) - C(63) - C(64) - C(65)	-3.3(8)
P(4) - C(63) - C(64) - C(65)	-176.2(4)
C(63) - C(64) - C(65) - C(66)	0.1(9)
C(64) - C(65) - C(66) - C(67)	2.0(9)
C(65) - C(66) - C(67) - C(68)	-0.8(9)
C(64) - C(63) - C(68) - C(67)	4.5(7)
P(4) - C(63) - C(68) - C(67)	178.0(4)
C(66) - C(67) - C(68) - C(63)	-2.5(7)
C(63) - P(4) - C(69) - C(74)	121.7(3)

C(75) - P(4) - C(69) - C(74)	-131.0(3)
Ru(2) - P(4) - C(69) - C(74)	-7.9(4)
C(63) - P(4) - C(69) - C(70)	-56.0(4)
C(75) - P(4) - C(69) - C(70)	51.4(4)
Ru(2) - P(4) - C(69) - C(70)	174.5(3)
C(74) - C(69) - C(70) - C(71)	-0.5(6)
P(4) - C(69) - C(70) - C(71)	177.3(4)
C(69) - C(70) - C(71) - C(72)	-0.7(7)
C(70) - C(71) - C(72) - C(73)	1.0(7)
C(71) - C(72) - C(73) - C(74)	-0.1(7)
C(72) - C(73) - C(74) - C(69)	-1.2(6)
C(70) - C(69) - C(74) - C(73)	1.5(6)
P(4) - C(69) - C(74) - C(73)	-176.2(3)
C(63) - P(4) - C(75) - C(80)	140.7(3)
C(69) - P(4) - C(75) - C(80)	37.6(4)
Ru(2) - P(4) - C(75) - C(80)	-90.4(3)
C(63) - P(4) - C(75) - C(76)	-50.2(4)
C(69) - P(4) - C(75) - C(76)	-153.3(3)
Ru(2) - P(4) - C(75) - C(76)	78.7(4)
C(80) - C(75) - C(76) - C(77)	-3.7(7)
P(4) - C(75) - C(76) - C(77)	-172.9(4)
C(75) - C(76) - C(77) - C(78)	1.7(8)
C(76) - C(77) - C(78) - C(79)	1.0(8)
C(77) - C(78) - C(79) - C(80)	-1.6(8)
C(76) - C(75) - C(80) - C(79)	3.1(7)
P(4) - C(75) - C(80) - C(79)	172.4(4)
C(78) - C(79) - C(80) - C(75)	-0.5(8)
C(93) - P(5) - C(81) - C(82)	-5.3(4)
C(87) - P(5) - C(81) - C(82)	101.7(4)
Ru(2) - P(5) - C(81) - C(82)	-133.9(3)
C(93) - P(5) - C(81) - C(86)	180.0(3)
C(87) - P(5) - C(81) - C(86)	-73.1(3)
Ru(2) - P(5) - C(81) - C(86)	51.3(3)
C(86) - C(81) - C(82) - C(83)	-1.1(7)
P(5) - C(81) - C(82) - C(83)	-175.7(4)
C(81) - C(82) - C(83) - C(84)	0.2(7)
C(82) - C(83) - C(84) - C(85)	0.4(7)
C(83) - C(84) - C(85) - C(86)	0.0(7)
C(84) - C(85) - C(86) - C(81)	-0.9(7)
C(82) - C(81) - C(86) - C(85)	1.4(6)
P(5) - C(81) - C(86) - C(85)	176.5(3)
C(93) - P(5) - C(87) - C(88)	101.6(4)
C(81) - P(5) - C(87) - C(88)	-6.1(4)
Ru(2) - P(5) - C(87) - C(88)	-131.8(4)
C(93) - P(5) - C(87) - C(92)	-79.7(4)
C(81) - P(5) - C(87) - C(92)	172.7(3)
Ru(2) - P(5) - C(87) - C(92)	46.9(4)
C(92) - C(87) - C(88) - C(89)	0.6(7)
P(5) - C(87) - C(88) - C(89)	179.4(4)
C(87) - C(88) - C(89) - C(90)	1.3(8)
C(88) - C(89) - C(90) - C(91)	-2.0(8)
C(89) - C(90) - C(91) - C(92)	0.7(8)
C(90) - C(91) - C(92) - C(87)	1.2(8)
C(88) - C(87) - C(92) - C(91)	-1.9(7)
P(5) - C(87) - C(92) - C(91)	179.3(4)
C(81) - P(5) - C(93) - C(94)	123.3(4)

C(87) - P(5) - C(93) - C(94)	18.6(4)
Ru(2) - P(5) - C(93) - C(94)	-107.4(3)
C(81) - P(5) - C(93) - C(98)	-59.2(4)
C(87) - P(5) - C(93) - C(98)	-163.9(3)
Ru(2) - P(5) - C(93) - C(98)	70.1(3)
C(98) - C(93) - C(94) - C(95)	-0.4(7)
P(5) - C(93) - C(94) - C(95)	177.2(4)
C(93) - C(94) - C(95) - C(96)	1.4(7)
C(94) - C(95) - C(96) - C(97)	-1.0(7)
C(95) - C(96) - C(97) - C(98)	-0.5(7)
C(96) - C(97) - C(98) - C(93)	1.5(6)
C(94) - C(93) - C(98) - C(97)	-1.1(6)
P(5) - C(93) - C(98) - C(97)	-178.8(3)

Symmetry transformations used to generate equivalent atoms: